NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

**USER-CENTERED ITERATIVE DESIGN OF A
COLLABORATIVE VIRTUAL ENVIRONMENT**

by

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March 2001

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13. ABSTRACT *(maximum 200 words)*

Most tasks that are desirable to train in a virtual environment are not tasks that we do alone, but rather are executed collaboratively with one or more team members. Yet little is known about how to construct virtual environment training systems that support collaborative behavior. The purpose of this thesis was to explore methodologies for developing collaborative virtual environments for training. Our approach centered on analyzing task or training specific requirements for the simulation environment. We applied user-centered design techniques to analyze the cognitive processes of collaborative wayfinding to develop interface design guidelines. We utilized the results of our analysis to propose a general model of collaborative wayfinding. This model emphasizes team collaboration and interaction in problem solving and decision-making. We tested the model in the field, using cognitive task analysis methods to study land navigators. This study was intended to validate the use of user-centered design methodologies for the design of collaborative virtual environments. Our findings provide information useful to design, ranging from model enhancement to interface development. We have explored the cognitive aspects of collaborative human wayfinding and design for collaborative virtual environments. Further investigation of design paradigms should include cognitive task analysis and behavioral task analysis.

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USER-CENTERED ITERATIVE DESIGN OF A COLLABORATIVE VIRTUAL ENVIRONMENT

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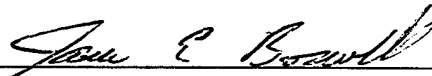Lieutenant Commander, United States Navy
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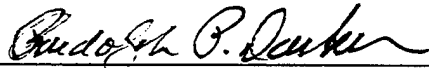
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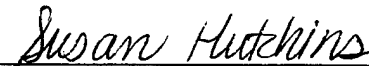## NAVAL POSTGRADUATE SCHOOL
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iii

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ABSTRACT

Most tasks that are desirable to train in a virtual environment are not tasks that we do alone, but rather are executed collaboratively with one or more team members. Yet little is known about how to construct virtual environment training systems that support collaborative behavior. The purpose of this thesis was to explore methodologies for developing collaborative virtual environments for training. Our approach centered on analyzing task or training specific requirements for the simulation environment. We applied user-centered design techniques to analyze the cognitive processes of collaborative wayfinding to develop interface design guidelines. We utilized the results of our analysis to propose a general model of collaborative wayfinding. This model emphasizes team collaboration and interaction in problem solving and decision-making. We tested the model in the field, using cognitive task analysis methods to study land navigators. This study was intended to validate the use of user-centered design methodologies for the design of collaborative virtual environments. Our findings provide information useful to design, ranging from model enhancement to interface development. We have explored the cognitive aspects of collaborative human wayfinding and design for collaborative virtual environments. Further investigation of design paradigms should include cognitive task analysis and behavioral task analysis.

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TABLE OF CONTENTS

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LIST OF FIGURES

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LIST OF TABLES

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LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

ACTA	Applied Cognitive Task Analysis
AI	Artificial Intelligence
ANSI	American National Standards Institute
CDI	Critical Decision Incidents
CDM	Critical Decision Method
CTA	Cognitive Task Analysis
CVE	Collaborative Virtual Environment
DGPS	Differential Global Positioning System
DOB	Date Of Birth
DOD	Department of Defense
GPS	Global Positioning Systems
HMD	Head Mounted Display
IEEE	Institute of Electrical and Electronics Engineers
IP	Initial Point
ISO	Industry Standards Organization
LORAN	Long Range Aid to Navigation
MOVES	Modeling Virtual Environments and Simulation
ONR	Office of Naval Research
RPD	Recognition Primed Decision
SEAL	Sea Air Land (U.S. Navy Special Forces)
SERE	Survival Evasion Resistance and Escape
SME	Subject Matter Experts
SMM	Shared Mental Models
TCP	Transmission Control Protocol
VE	Virtual Environments

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I. OVERVIEW

A. THESIS STATEMENT

A detailed cognitive model of collaborative interactive activity can be used as the basis for design of an interactive interface to support virtual environments requiring human collaboration.

B. MOTIVATION

Virtual environment (VE) applications are achieving widespread use in the military. Military VE applications include theater planning, training, and mission rehearsal (DeBrine & Morrow, 2000). Virtual environments have garnered increased funding and attention in the last decade as a possible replacement or addition to some training paradigms. Little work has been done on the design of interactive components of virtual environments (Hix, Swann, Gabbard, McGee, Durbin, & King, 1999). Most of the engineering effort, in terms of both research and investment, has been on development of visual quality and rendering efficiency. Little is known about what makes effective interaction possible in a VE, or how behavior in VEs translates to the real world. A behavior in virtual environments that has been studied extensively is wayfinding. Wayfinding is the process of understanding the spatial relationships in an environment and planning and executing a route of travel. How this behavior works under collaborative conditions in either virtual environments or real world environments has not been studied.

1. User Centered Design

The limitations of current virtual environment technology for conveying spatial awareness, a sense of presence and realistic immersion are well documented. The goal of a technological approach is to provide an "artificial reality," an experience that is indistinguishable from reality. We would argue that a more productive approach to improving collaborative virtual environments is through user-centered interface design. This approach to design can focus the engineering effort on supporting particular training aspects or specific tasks through modeling and study of the task's cognitive and team requirements. The usefulness of virtual environments for training may be greatly enhanced through careful and methodical design of the user interface. For instance, what cues used in communication and collaboration in real world environments are not available in the virtual environment, resulting in less effective collaboration? Do participants substitute artificial cues, or do they overcome shortcomings in the virtual environment with other methods and do these methods transfer to a real world task? Is the collaborative method modified or enhanced? Military training applications that use virtual environments may require interactive collaboration to effectively teach a broad scope of skills. Design methods used to develop collaborative interfaces may be critical to broadening the usability of modern VE hardware and software in the training arena. The effect of hardware and software limitations on collaboration should be examined to guide the development and usage of virtual environments for training purposes. A methodology for developing interfaces designed to provide collaborative interaction should be developed to enable system designers to accurately and concisely model collaborative training paradigms.

2

2. Military VE Applications

Military use of simulators has grown markedly in the last decade, moving from ultra-expensive flight simulators to integrated combat system simulators to collaborative virtual environments. The design approaches used for flight simulators and integrated combat trainers have followed traditional engineering methods. The engineering effort concentrated on recreating a realistic cockpit or computer interface and providing simulated visual and information displays. Interactive collaboration design may require a subtly different approach. Rigorous engineering standards applied to the problem of recreating face-to-face interaction may prove intractable and extremely costly to overcome. However, studies in the last decade on interface design and collaborative teamwork may provide an efficient bridge between technological capabilities and training requirements. Virtual environments utilizing some measure of immersion to train personnel on specific tasks may range from land navigation training to mission simulation to architectural walkthrough (familiarization training). Another reason to study this method of interface design is DOD's investment in creating a network-centric force. Eventually the soldier or sailor in the field may require augmented display of information, that is, data that is displayed over the visual field of the user. Studying the collaborative nature of team-oriented tasks may provide insight regarding methods of augmenting performance, providing useful information in a usable and easily understood format.

3. Teamwork and Collaboration

Teamwork is essential to most military tasks; sharing information and sharing goals is a primary focal point of nearly every tactical operation. The U.S. Navy has

invested heavily in the study of teamwork and interface development over the last decade through the TADMUS (Tactical Decision Making Under Stress) program. This program was initiated following the USS Vincennes accidental shoot-down of an Iranian airliner. TADMUS was a seven year research project designed to develop training, decision support, and information display principles that would help to mitigate the impact of stress on decision making. A significant portion of this research was devoted to methods of designing interfaces to support decision-making. This research concentrated on building cognitive models of the team processes requiring decision support, and designing interfaces based on those models. While the Aegis system is not a virtual environment per se, it does represent virtual knowledge, that is, three-dimensional spatial understanding is a basic requirement for the display systems. The methodologies utilized by TADMUS researchers to study and model team related tasks are significantly relevant to the study and modeling of human interactive collaboration for the design of virtual environments.

C. APPROACH

We began this research with the goal of utilizing an existing cognitive model of human navigation as a source for the design of interactive interface elements for a virtual world. Review of the relevant literature, however, failed to uncover a complete and accurate cognitive model of human navigation. Several partial models were discovered, as well as other research that significantly aided in building an initial model. An initial model was developed using only the information gleaned from previous research. We decided that in order to fill in the details of our partial model of human collaboration in navigation and wayfinding we should study subjects in an experimental setting.

Our goal was to develop a model of human collaboration in navigation/wayfinding as the basis of designing interface elements for a virtual world. Subjects were studied performing navigation tasks as a team in the field, we collected detailed information on interaction techniques, collaboration and communication. This study was used as the basis for developing design guidelines for interactive collaborative virtual environments that might support wayfinding.

D. THESIS ORGANIZATION

The remainder of this thesis is organized as follows:

Chapter II: Background. Chapter II provides the reader with a background in the technical areas of this thesis. It also includes an analysis of previous related work in this field.

Chapter III: Theoretical Model of Collaboration. This chapter outlines the research used to design our initial model of collaboration and the model itself.

Chapter IV: Collaborative Navigation. Chapter IV provides a detailed description of our field experiment and the design of the modified collaborative navigation model.

Chapter V: Field Study Results. Chapter V discusses the results of our field study.

Chapter VI: Discussion, Recommendations, and Conclusions. Chapter VI provides an analysis of the implications of our results, recommendations for designing a CVE to support wayfinding tasks, and future work in this field.

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II. BACKGROUND AND RELATED WORK

A. INTRODUCTION

This chapter offers the reader sufficient background to appreciate the methodology of this work. The first section is devoted to human navigation and wayfinding. Recent relevant work on teamwork and collaboration is discussed in the second section.

B. HUMAN NAVIGATION AND WAYFINDING

In general there are two types of guiding processes used by humans. The first of these processes, used to guide vessels over large water bodies or to fly aircraft, is called navigation. Navigation means to steer or direct a ship or aircraft (Webster, 1995). The second type of guiding process is used in following a path or route between an origin and a destination and is called wayfinding. Wayfinding generally refers to "land navigation." It is purposive, directed and motivated activity (Golledge, 1999). Wayfinding involves selecting paths from a network of possible paths. For successful travel it is necessary to identify origin and destination, to determine turn angles, to identify segment lengths and directions of movement, to recognize route and distant landmarks and to embed the route to be taken in some larger reference frame (Golledge, 1999). This aspect of human activity is used extensively in the infantry environment and has been identified as a task that might be effectively and efficiently trained using virtual environments (U.S. Army Technical Report 1754, 2000).

1. Spatial Knowledge and Wayfinding

Human wayfinding, and the acquisition of spatial knowledge in a natural environment, has been thoroughly researched and a basic model of human wayfinding

7

has begun to emerge. While there are several proposed models of wayfinding, they are quite comparable and can serve as a benchmark or jumping off point for further exploration of the subject. Simon R. Goerger provides a concise and accurate description of the current theory of spatial knowledge in his recent work (Goerger, 1998):

> Spatial knowledge or spatial cognition is a mental representation of a real or virtual environment (Wickens, 1992). Figure 2. 1 graphically displays Thorndyke's theory on human acquisition of spatial information to build a mental representation of the world (Thorndyke, 1980). In this model the classifications of landmark, route, and survey knowledge are not mutually exclusive; knowledge at higher levels builds upon and augments knowledge gained from the preceeding levels.
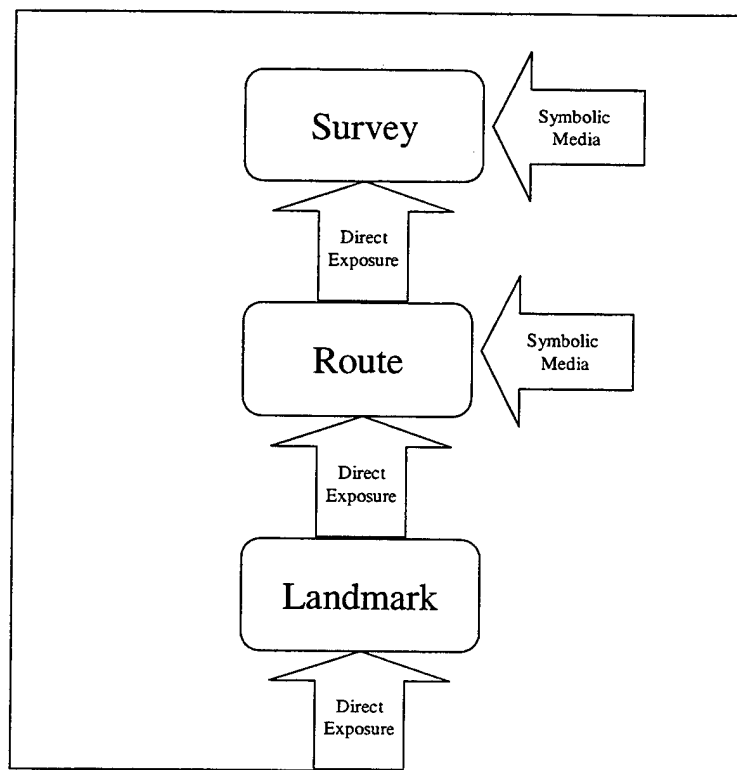
Figure 2. 1 Navigation Knowledge

Landmark knowledge is identified as the ability to recognize distinctive features associated with a specific location in the environment. This level of navigation knowledge is associated with the ability to store features such as specific hilltops or road intersections in memory and

recognize them. Landmark knowledge is acquired through the direct observation of objects in the environment. It can also be gained through indirect observation of the objects in a medium such as a photograph. Successful landmark knowledge is demonstrated by the ability to recognize individual locations or unique objects within a environment (Darken 1995; Thorndyke, 1980).

Route knowledge is defined as the procedural knowledge required to navigate along a route or path between landmarks or distant locations (Golledge, 1991). It is derived from the ability to expand landmark knowledge into a larger more complex arrangement of linked objects. Route knowledge is based on an egocentric (inside-out) viewpoint and is demonstrated by the ability to move from one landmark to another along a prescribed path. Route knowledge can be gained through repeated exposure to an environment map or through simulated exposure to the environment via a medium such as video (Goldin & Thorndyke, 1982).

Finally, survey (or configurational) knowledge is the highest level of spatial knowledge. It represents a map-like or top-down mental encoding of the environment and is based on an exocentric (outside-in) viewpoint. This last form of spatial knowledge is usually gained through map study but, can also be gained through extensive and repeated exposure to the environment (Thorndyke, 1980). Survey knowledge can be demonstrated by an individual's ability to describe the relative locations and the distances between landmarks or by devising new routes between landmarks even though the person has never traveled a route between them (Banker, 1997).

Thorndyke's theory dipicts the accumulation of wayfinding skill in layers which can be construed as filtering one's understanding of the environment. Each layer "builds upon" and affects the next layer in the model. Decisions aren't just based upon landmark knowledge, route knowledge, or configurational knowledge, but on their continuous interaction. While an individual may have limited configurational knowledge this aspect of spatial understanding will still have an impact of some kind on his or her decisions.

Golledge (1999) argues that "much of human common sense and expert knowledge of space is traditionally represented as a Euclidean metric." Given this emphasis, the basic geometry of spatial representations and cognitive maps can be

summarized in terms of points, lines, areas, and surfaces. Consequently, if it is assumed that training and experience help structure cognition then it also seems reasonable to assume that as environmental learning occurs, some of the standard geometry of identifiable physical space will be included in its cognitive representation (Golledge, 1999).

2. Cognitive Maps

The cognitive map is a concept coined by Tolman (1948) and is used to specify the internal representation of spatial information. The basic idea of a cognitive map is that humans collect information on an environment by gradually remembering points (such as landmarks and reference nodes), lines (including routes, paths, and tracks), areas (for example regions, neighborhoods, and topological containment or inclusion) and surfaces (some three dimensional characteristic or features of places such as density) (Golledge, 1990). This information is accumulated gradually, in most cases, as individuals make mental connections and gather data about their environment to form a spatial cognitive map.

There are many ways that one can learn an environment (Tellevik, 1992). When the environment is new, novel, or un-experienced, possible learning strategies include (1) active search and exploration according to specific rules or heuristics, (2) a priori familiarization with secondary information sources about the environment (such as maps, sketches, written or verbal descriptions, artists' renderings, videos, photographs, photographic slides, movies and virtual realities) (MacEachren, 1991); and (3) experience of the environment using controlled navigational practices (including exploration using path integration to maintain knowledge of a home base, exploration and retrace methods, exploration by boundary following, sequenced neighborhood search, and so on). Only

10

humans appear to have regular access to communicate materials of the type listed in (2) above (Golledge, 1999).

Shortcutting is an example of following a route that implies some type of survey, layout, or configurational knowledge has been achieved. The process of changing a route based on understanding one's location and the environment, can be taken as a sign of some sort of Euclidean mapping of the environment. Such an inference is made even stronger if at any point on the return home the individual can indicate the direction and approximate distance from the current location to a landmark, place, or choice point, experienced on, or visible from, the initial route (Golledge, 1999).

Humans developed cognitive maps to answer questions such as: Where am I? Where is my home base? Where are the phenomena for which I am searching? How do I select a route between places? How do I return home? How do I know when I'm lost? These questions form the basis of navigation, of why we navigate, and therefore serve as the motivation for compiling cognitive maps (Golledge, 1999).

3. Prior Studies of Spatial Knowledge and Virtual Environments (VEs)

a. Goerger's Model

Banker (1997) studied virtual environment (VE) model training transfer in a natural environment. His study consisted of three treatment groups performing wayfinding tasks in a natural environment after studying with map study, map and VE study, or actual environment study. The three groups of individuals performed similar navigation tasks in a natural environment after training with one of the methods. Banker classified his participants using a short questionnaire to elicit information about their experience with wayfinding. He found that navigational ability had a more pronounced

effect on performance than did study method. However, among the treatment groups, the intermediate ability group seemed to benefit the most from the VE training. He also found that novices were overloaded by the excess workload of using a VE and that advanced navigators found the VE to be minimally useful. His results did indicate that a properly designed VE could impart familiarity with a selected natural environment better than map study alone, for all except the most advanced land navigators (Banker, 1997). However, these findings may be specific to this particular VE environment. Another VE may be of more benefit to novice or more advanced users.

Goerger (1998) conducted a similar study finding that the VE was an effective tool for gaining familiarity with a natural environment, however, his data showed no statistical improvement between VE and map, and map only study. Goerger also found that spatial ability played a more significant role in performance than study method. Goerger proposed a model (Figure 2.2) of the navigation process based on his research and partially on Wickens (1998).

Figure 2.2 outlines distinct types of wayfinding knowledge such as route planning, route navigation, navigational aids, and error recovery. It is important to make two notes at this point: 1) This model was proposed in an annex at the end of Goerger's work and was not the focus of his experiments, and 2) Goerger seems to have approached the process of wayfinding from the activity perspective, that is, what humans do, or need to do, in each step of the process. This model concentrates on describing the "actions" required during the process, thoroughly and convincingly, but leaves some of the cognitive conceptualizations such as how the mental map affects route planning or route navigation untouched. Goerger proposed the important idea that actual route navigation

occurs in two different phases: fine movement and course movement. Course movement occurs during the intermediate steps of navigation. Its goal is never to locate the target but to provide rough guidance to a "general locale." Course movement might use large easily identifiable landmarks such as a road or telephone line as a way of honing in on the
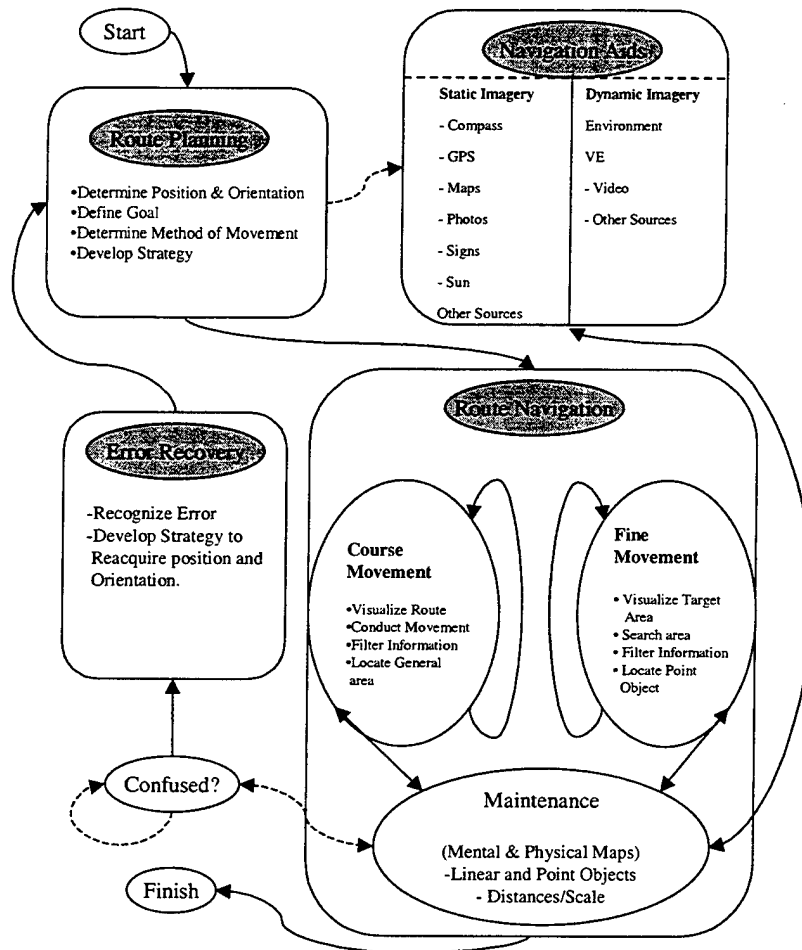
Figure 2.2 Goerger's Wayfinding Model (From: Goerger, 1998)

final goal. Fine movement occurs once course movement has been accomplished and the navigator determines high proximity to the final goal. Attention shifts to the details of the target, the target's exact location, description, and any additional information that might describe its location - pictorial, verbal or otherwise. This finding is very

interesting because it further divides the task of physical movement into two identifiable sub-processes which have distinct recognizable patterns and actions.

b. The Chen and Stanney Wayfinding Model

Chen and Stanney (1999) proposed a theoretical model (Figure 2.3) of wayfinding for use in guiding the design of navigational aiding in virtual environments. Their model is based on studies of wayfinding in natural environments and divides the wayfinding process into three main sub-processes: cognitive mapping, wayfinding plan development, and physical movement or navigation through the environment. This model represents human navigation as a loop structure that revisits each sub-process until the goal of the navigation is reached. It differs slightly from the Goerger model in that it does not include error recovery as a distinct sub-process and it directly emphasizes the cognitive processes involved. Chen also proposed a taxonomy of navigational tools to aid in the design of specified wayfinding sub-processes. These categories were based on the effect different tools were thought to have on the wayfinding process.

1. Tools that can display an individual's current position.

2. Tools that can display an individual's current orientation.

3. Tools that can log an individual's movements.

4. Tools that can demonstrate the surrounding environment.

5. Guided navigational systems.
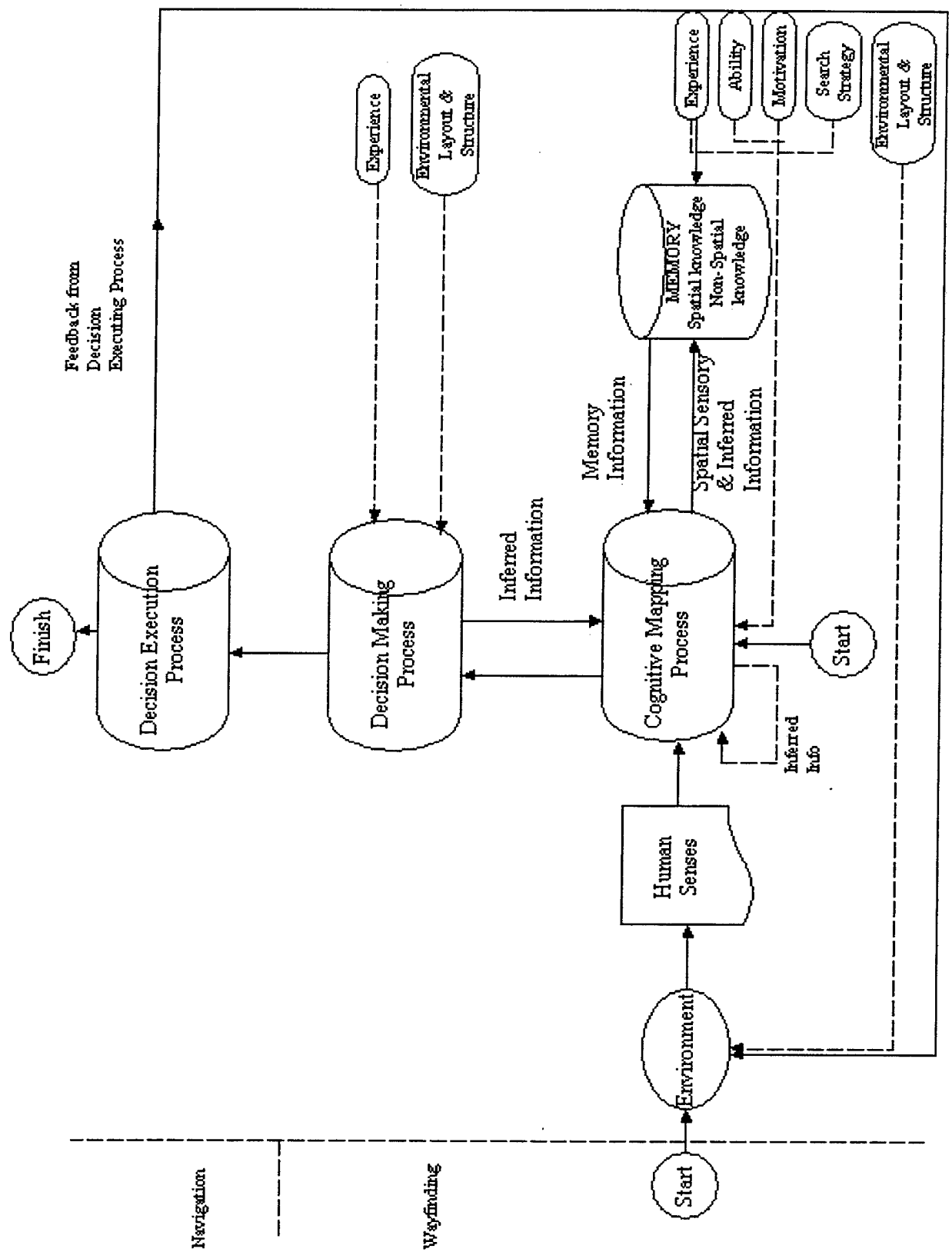
Figure 2.3 Chen and Stanney Wayfinding Model (From: Chen & Stanney, 1999)

15

Category 1 tools include such systems as global positioning systems (GPS) and LORAN, which provide exact location data. Compasses or landmarks are considered category 2 tools and can direct an individual's orientation. Category 1 and 2 tools assist inperforming spatial-orientation tasks such as navigation in a natural environment. Some GPS units serve as category 3 tools providing not only orientation and position, but also displaying location information on map and logging it for future use. Category 4 includes topographical maps, graphical displays (some GPS units), CRT display, and other media, which provide a physical view or depiction of the environment. Category 5 contains such items as sign-posts, auto-pilots, and GPS route planners.

These categories may prove useful in the process of determining which types of tools might be included in a virtual environment. However, the exact determination of the effect of specific tools on the cognitive model is elusive in documentation on the subject. This vagueness makes the implementation and use of the Chen and Stanney categories questionable and requires further research.

c. Darken's Model

Darken (1999) proposed a highly detailed model (Figure 2.4) of human navigation in which he describes how each element of the navigation model continuously interacts with, and affects, the other elements. His model is a partial melding of work in cognitive psychology by Neisser (1976), and works in human navigation in virtual environments by Jul & Furnas (1997), and is based on original research on the cognitive aspect of human wayfinding conducted at the Naval Postgraduate School.

Darken's model begins with goal formulation as the driving factor in all navigation tasks. The goal affects and directs all supporting behavior in navigation.

Goals are developed and modified continuously based on the mental model of the environment, progressing from initial and supporting goals, through intermediate goals, to the overarching inclusive goal of a navigation process. Strategy follows goal definition and is described by Darken as a continuously evolving process. Strategies are developed, modified, and discarded continuously, as perception of the environment and subsequent assessment modify the mental model. Strategies are the driving force for intermediate goals. For instance, an example of strategy might be developing intermediate goals intended to expand the information base or test a hypothesis.

This model of navigation has at least two important aspects that bear discussion. Darken develops the idea that a layering of distinct cognitive processes drives interaction with the environment: goal formulation, strategy development, and perception. This process might be labeled the perception/reaction loop. Procedural layering implies parallelism, the layers are interactive and independent, allowing the human mind to simultaneously analyze and solve multiple levels of the same problem. Environmental interaction (locomotion->perception->environment->assessment) is the foundation layer of the navigation loop and forms the basis for using and modifying the mental model of the environment. A second important observation by Darken is that error recovery is a sub-process that starts with a new goal of correcting the error and uses the environment and mental model from the primary goal process. Darken's assessment of the interaction of the underlying aspects of the navigation process is "that locomotion affords sampling of the environment via perception. The environment modifies the mental model via assessment. And the mental model directs locomotion."

GOAL FORMULATION:
nav task specification
nav task decomposition

STRATEGY:
coarse movement
fine movement
route planning
External data acquisition
map reading
compass reading
sign reading, etc

PERCEPTION:
orientation (bearing estimation)
Depth perception (distance estimation)
multi-modal cues

VIA

LOCOMOTION:
feedback: kinesthetic,
vestibular
optical flow
exertion
direct/passive control
Travel mode(fly, drive ,walk)

SAMPLES

ASSESSMENT:
progress evaluation
error recognition
maintenance

VIA

ENVIRONMENT:
scale
dimensionality
stimuli density
structure
clustering
object orientation
boundaries
occlusion/movement restriction

MODIFIES

DIRECTS

MENTAL MODELING:
memory
hierarchical spatial memory
working memory
salience of cues

INDIVIDUAL DIFFERENCES:
a priori spatial knowledge
inferencing ability
spatial ability
mental rotation (perspective transformation)
perceptual speed, etc.
learning style
confidence
experience (perceived ability)
map simplification ability
dead reckoning
ability to generalize over terrain types

ERROR RECOVERY:
This is an iterative sub-process starting with a new goal formulation where the goal is the recovery of the error. While the subtask may be considered as different from the primary task, the environment and mental models are identical to those in the primary task.

MAINTENANCE BEHAVIOR:
This is a single level subtask (non-recursive) or iterative) where the goal is to confirm the mental model via a secondary navigation task. If successful, then continue, if failure, then exit maintenance and resume primary task at strategy.

Figure 2.4 Darken's Model of Human Navigation

d. Other Studies

Recent research at the Army Research Institute on training transfer found that significant spatial learning occurred as a result of training in a virtual environment (Witmer, Bailey, and Knerr, 1995). The results indicated that spatial skills acquired in a virtual environment transfer to real-world settings if the virtual environment adequately represents important landmarks and stimulus cues.

Bliss, Tidwell, and Guest examined the use of VE technology in acquiring spatial knowledge as outlined in Thorndyke's model (Bliss, et al., 1997). The Bliss, et al. study found that subjects gained better landmark and route knowledge from a VE than from map study alone.

Chase (1983) conducted research on the differences in spatial knowledge acquired from map study and from exposure to the actual environment. His research indicated that individuals with repeated exposure to the environment had better landmark and route knowledge and individuals who conducted map study had better survey knowledge. Chase concluded that repeated exposure to an environment provides route and landmark knowledge but this experience does not necessarily translate into increased survey knowledge. The implication of this finding is that some combination of VE and map interaction might be required to form a complete mental map of an environment.

Singer, Allen, McDonald and Gildea (1997) investigated spatial training transfer to compare different levels of VE immersion to map study. Singer, et al., studied personnel performing navigation tasks in a natural environment after training using three different methods of study. The first was termed a Hi-VE, and used a high-fidelity model, projected using a Stereoscopic Head Mounted Display (HMD) with fully head-coupled

19

gaze control and treadmill-based movement control. The Low-VE configuration consisted of the same HMD with both gaze control and viewpoint movement controlled by a joystick. The third method included using a control group which studied only topographical maps as a way to gain familiarity with the environment. Their study showed that the more interactive experience provided better spatial knowledge transfer. More normal interactions, with cues supported by the virtual environment, seems to support better spatial recognition and knowledge of specific landmarks than can be acquired through purely cognitive exercises with symbolic (topographical maps) representation of terrain (Singer, et al., 1997).

Stine (2000) studied the mental model of expert navigators using the Critical Decision Method (CDM) of knowledge elicitation. He formed a limited cognitive model of expert tactical land navigation by studying U.S. Army Special Forces students in the field and performing CDM after action debriefs. His study showed that the four important characteristics of experts were: (1) they rely on high-fidelity mental maps, (2) they blend multiple cues from the environment, (3) they dynamically calibrate and adjust navigational tools; and (4) they spatially visualize three-dimensional terrain. While Stine did not elaborate his discussion of the mental model with a graphical depiction, his analysis generally supports the models discussed previously.

4. Summary of Spatial Knowledge and Wayfinding

A great deal has been learned during the last twenty years about how humans gather and retain spatial information. The study of this subject has produced a comprehensive, although not yet complete, understanding of the cognitive and physical mechanisms involved in human wayfinding. An actual model of human wayfinding has

not yet been widely accepted in the research community, yet the models proposed thus far have intriguing similarities. Based on these similarities we believe an abstract model of human wayfinding might be adapted from the work that has been accomplished.

C. TEAMWORK AND COLLABORATION

In our study of a user-centered design methodology for collaborative wayfinding we would be remiss in not discussing the basics of team modeling and teamwork measurement. It should be clear that in designing a tool to improve coordinated performance and interaction in virtual environments the "team" aspect of organization and interaction is vital. Over the past several decades, tremendous resources have been applied to understanding team training and performance (Dickinson and McIntyre, 1997).

Dickinson and McIntyre (1997) reviewed the teamwork literature and developed a general model (Figure 2.5) of team processes. They identified and defined seven core components of teamwork depicted in Figure 2.5, which we will discuss in detail. Communication involves the exchange of information between two or more team members and is often used to clarify, or acknowledge, receipt of information (Dickinson and McIntyre, 1997). Communication is thought to be the mechanism that links the other components of teamwork. Communication is widely identified as being critical to all aspects of team functioning (Stout, Cannon-Bowers, Salas, & Milanovich, 1999; Cooke, Salas, & Cannon-Bowers, 2000; Brannick, Prince, Prince, & Salas, 1995). Team members' understanding of individual responsibilities in communicating with each other can define the shared mental model for communication. Evidence supports the idea that teams perform more proficiently when their communication is well coordinated, with little excess chatter, and with concise statements, questioning, feedback, and confirmation

(Kraiger and Wenzel, 1997).

Team orientation includes the nature of the attitudes that team members have toward one another, the team task, team leadership, as well as their self-awareness as a
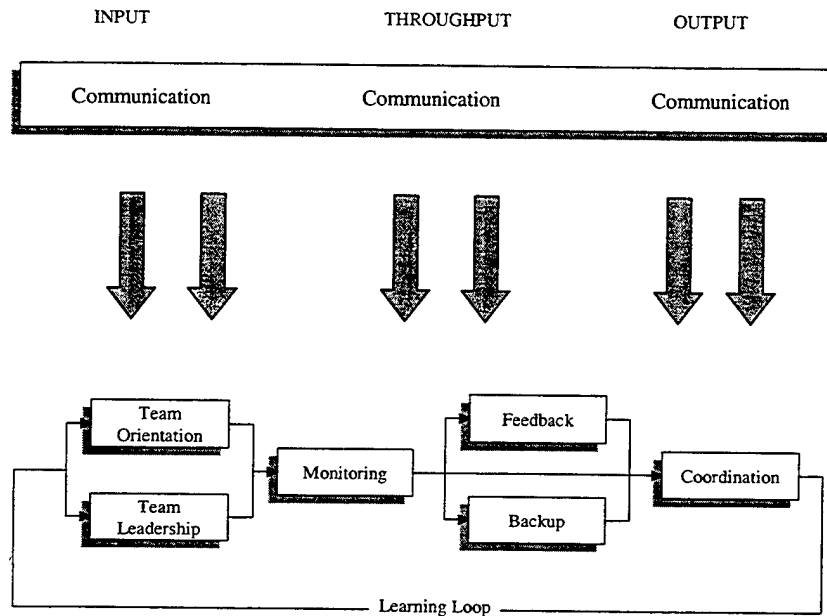
Figure 2.5 Model of Collaboration

team member and group cohesiveness (Dickinson and McIntyre, 1997). Stout, et al. (1999) addressed this aspect of teamwork in their discussion of Shared Mental Models (SMMs) and their importance to team processes. SMMs are thought to provide team members with a common understanding of who is responsible for what task and what the information requirements are for each team member (Stout, et al., 1999). It is widely believed that the SMM is the construct that allows team members to anticipate each other's information requirements and implicitly communicate in times of stress.

Team leadership is defined in Brannick, et al. (1995) as directing and coordinating the activities of other team members. It is not restricted to the functions of

22

the formal leader but spread throughout the team. Dickinson and McIntyre (1997) discuss team leadership in terms of the direction and structure provided by formal leaders and other members as well as the implication that planning and organizing activities have enabled members to respond as a function of the behaviors of others. Prince, Brannick, Prince and Salas (1997) found that effective flight crew leaders had consistent leadership behaviors such as establishing boundaries, defining the task, and having consistent leadership behaviors. It might be assumed that on specific team tasks, such as a flight crew or a fire fighting team, effective leaders have identifiable consistent behaviors, which greatly enhance their individual and team performance.

Monitoring of team performance is crucial to the team being able to adjust and adapt its strategies to achieve the team goal. Monitoring refers to the observation and awareness of the activities and performance of other team members. It implies that team members are individually competent and that they may subsequently provide feedback and backup behavior (Dickinson & McIntyre, 1997). This component is critical in providing a pathway for coordination and adaptation.

Feedback is the critical discussion of performance among team members. This component requires team members to honestly evaluate and critique team performance and assumes monitoring. Tannenbaum, Smith-Jentsch, and Behson (1998) found that feedback in the team learning cycle is critical to improving coordination and generating trust among team members. Specifically, they found that leaders who are quick to acknowledge their own shortcomings are able to generate similar interactions from other team members. In addition to self-critiquing, leaders and team members must accept and encourage constructive peer criticism to facilitate improvements in team performance.

23

Backup behavior involves team members helping other team members perform assigned tasks and requires an implied degree of cross training as well as monitoring and self-awareness. A shared understanding of the task goals, team members' roles, and how and why the team operates as it does may be the basis for implicit coordination (Cannon-Bowers, Salas, & Converse, 1993). Backup behavior may be dependent on the level of cross training within a team. If a team member is comfortable with his or her responsibilities and understands the responsibilities of others, he or she is more likely to contribute under conditions of stress or overload.

Finally, the coordination component of the teamwork model ties together the effective implementation of the other components. Coordination is identified as the synchronization of efforts and abilities to achieve the team goal. Stout, et al. (1999) identify coordination as the outcome of successfully achieving a high degree of shared mental model. This level of a SMM provides for implicit communication and implicit coordination making such critical components of teamwork as feedback and backup automatic.

Above all else, teamwork requires effective communication, but the interplay of planning, leadership, team goals, and individual goals is critical to overall performance. Backup and feedback are acquired components expected in teams that are performing at a high level of coordination and efficiency. Coordination appears to be the outcome of successful communication strategies combined with the development of the other components of the model. Coordination is a strong measure of a team's effectiveness. While aspects of this model find general support throughout the literature it is not exact or expected to be complete and whole as a model of human interaction through teams.

This is a general model of teamwork and collaboration awaiting application to specific circumstances.

D. SUMMARY

Wayfinding as a human endeavor has been widely studied for many years, generating a tremendous amount of information about the processes of the human mind in performing the various tasks required. Numerous models have been proposed to facilitate understanding of the wayfinding process in humans. While no one model is considered complete, or totally accurate by the human navigation research community, the models proposed share considerable similarities. The team aspect of wayfinding behavior has not been studied in terms of either developing a cognitive model of the team, or of delineating characteristics of team behavior during wayfinding activities. It is possible that a generalized model of wayfinding, combined with the model of team performance supplied by Dickinson and McIntyre (1997) may provide a suitable starting point for the examination of team wayfinding behavior. This model could then be tested for validity, and revised or discarded based on the data obtained. Once validated, or adapted sufficiently, it might then be used to develop interface elements to more effectively and efficiently support the behavioral requirements of collaborative wayfinding in virtual environments.

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III. THEORETICAL MODEL OF COLLABORATION

A. INTRODUCTION

The purpose of this chapter is to introduce and explain our proposed model of collaborative navigation. This model is an attempt to provide the basis for examining wayfinding as a team process.

B. MODIFIED MODEL OF WAYFINDING

Chen (1999), Goerger (1998) and many other researchers have made considerable progress in providing a model that accurately describes the cognitive processes of human wayfinding. The various models are complementary and research in the area supports a generalized model of human wayfinding that, while not refined, is adequate to explore design methodologies intended to support this process.

1. Wayfinding as a Layered Model

The levels, or distinct sub-processes, of wayfinding have been identified through numerous studies (Golledge, et al., 1998; Darken, 1999; Goerger, 1998; Stine, 2000; Chen & Stanney, 1998; Raubal & Worboys, 1998). The taxonomy of wayfinding and human navigation varies across the spectrum of researchers and sub-specialties. But, in general, there are some clearly identifiable building blocks to the process, the details of which are still being investigated. Wayfinding as a process is typically divided into four processes; interaction with the environment, cognitive mapping, route planning, and route navigation. We believe that these levels, if viewed as layers (Figure 3.1) of a "wayfinding protocol" will present the designer a useful abstraction for understanding wayfinding and developing tools which to support it. This view of the model has interesting ramifications. Instead of viewing wayfinding as a serial process, it is viewed

27

as a layered protocol, much like the ISO seven layer model for TCP-IP on the Internet. Instead of viewing the layers as serially interactive, they might be viewed as object-oriented levels. This abstraction supports the idea of parallel process identified by Darken (1999) in his model. Parallel process in the ISO model interact but are not intertwined, the processes share output but not inner-function. The distinct layers or areas of the wayfinding process are supported throughout recent research on human wayfinding (Goerger, 1998; Darken, 1999; Timpf, et al., 1992; Vinson, 1999; Golledge, 1998). This distinction may not be scientifically exact, but it allows the abstraction of each layer in terms of interfaces and function.

This view takes human sensory perception and environment as the basic layer of the wayfinding model, much like the hardware connection is the basis of the TCP-IP model. This basis described by Darken (1999) is the underlying inter-related sub-process that is constantly in flux and includes perception, environment, and mental model. Goerger (1998) discusses Thorndyke's layered scheme as being continuously interactive, that is, that different levels of spatial understanding have a continuous impact on the others. We believe that the literature and studies of human navigation support a model that works more like the ISO Internet protocol in a layered fashion. In this model each layer performs certain aspects of the wayfinding task and interfaces with the other layers as needed. This layering of the major processes of wayfinding might work in the following fashion:

1.   The basis of wayfinding is human sensory perception and the environment; this is the lowest layer and serves as the physical connection.

2.   The Cognitive Map construct, which is the model of human spatial understanding of the environment, is the second layer of the wayfinding model. This layer is constantly updated, compared, and analyzed, while it filters understanding of the environment for other processes.

3.   Route Planning serves as the middle layer, bouncing ideas off of the Cognitive Map and comparing the environment to the Cognitive Map when new plans are needed. This layer develops wayfinding plans and serves as the basis of the Route Navigation Layer. Route Navigation compares the environment to Route Planning and the two layers continuously update and critique the Cognitive Map layer.

4.   The Route Navigation Layer is the active part of wayfinding. At this layer the plans developed from the previous layers are enacted with continuous feedback and comparison to the Planned Route and to the Cognitive Model.

A minor alteration from Chen and Stanney's model (Figure 2.3) is the annotation that motivation, experience, and ability (Individual Factors) play an important role in every part of the wayfinding model and are not limited to the cognitive mapping layer.

It is important to note that the Chen/Stanney and Goerger (Figure 2.2) models are comparable although not superficially so. Goerger, for instance, makes no direct mention of the cognitive map, but rather refers to it obliquely in each of his distinct areas of wayfinding. In Goerger's model the cognitive map is the background upon which the

Wayfinding Model

Finish

Route Navigation:
Course Movement
Fine Movement
Information Maintenance

Individual Factors

Develop Strategies
Update Location
Define Goals

Feedback & Comparison (Error Checking)
Visualize Route/Target Area
Filter Information
Update Map

Experience
Ability
Motivation

Route Planning:
Determine Position and Orientation
Define Goals
Determine Method of Movement
Develop Strategy

Feedback, Comparison & Update
Recognize Error
Determine Position

Cognitive Mapping Processes:
Accumulate Spatial Knowledge:
Landmark, Route and Survey
Identify Landmarks, Distances, Lines, Shapes
Memory Processes, Inferred Information

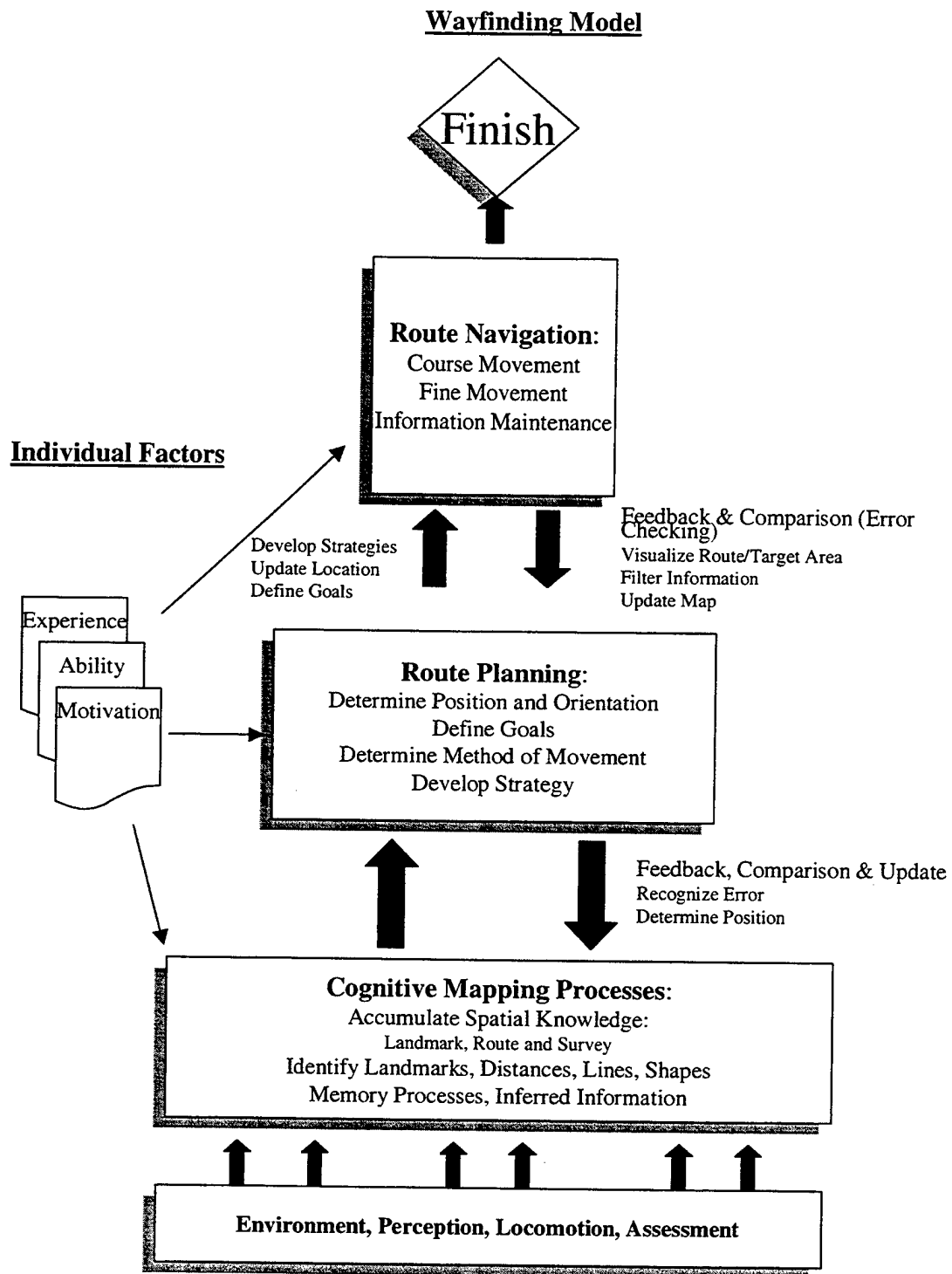**Environment, Perception, Locomotion, Assessment**

Figure 3.1 Human Wayfinding Model.

other aspects of wayfinding take place. This actually fits nicely with the Chen/Stanney model; Goerger's model concentrates on the "actions" of wayfinding - how do the layers interact, what is occurring and why. Chen and Stanney (1999) and Darken (1999) concentrate on the specific processes and an adaptation of these models may be more suitable for analysis and comparison to field studies.

2. Collaboration in Wayfinding

Our interest in wayfinding was based in terms of team coordination and collaboration. We began this exercise asking how one should go about the task of designing interface elements for virtual environments that require collaboration and coordination. Teamwork is another word for collaboration and coordination, and the general model presented by Dickinson and McIntyre (1998) serves nicely as a starting point for this investigation. Their model outlines the basic aspects of teamwork and discusses the requirements for successful teamwork.

How then does this model affect wayfinding? That is, how do the two interact, how do two people collaborate on a wayfinding objective, share responsibility and goal setting, provide monitoring, feedback, and backup? We believe that the communications aspect of the collaboration model can be viewed in a similar manner to Chen and Stanney's (1999) Navigation Tools. Communication serves as a tool or extension of ones ability (Figure 3.2). We acknowledge that many aspects of communication between humans are quite different from interaction with inanimate tools. This input-output aspect of interaction in wayfinding is the critical part of collaboration that we intend to study.

31

Communication as a construct of teamwork plays an important role throughout the teamwork model and can be examined in terms of its effect on wayfinding. What methods of communication then serve to support the accomplishment of wayfinding goals, while also acting in the collaborative effort of two or more individuals? We intend to examine communication as part of the collaboration model and its various effects on
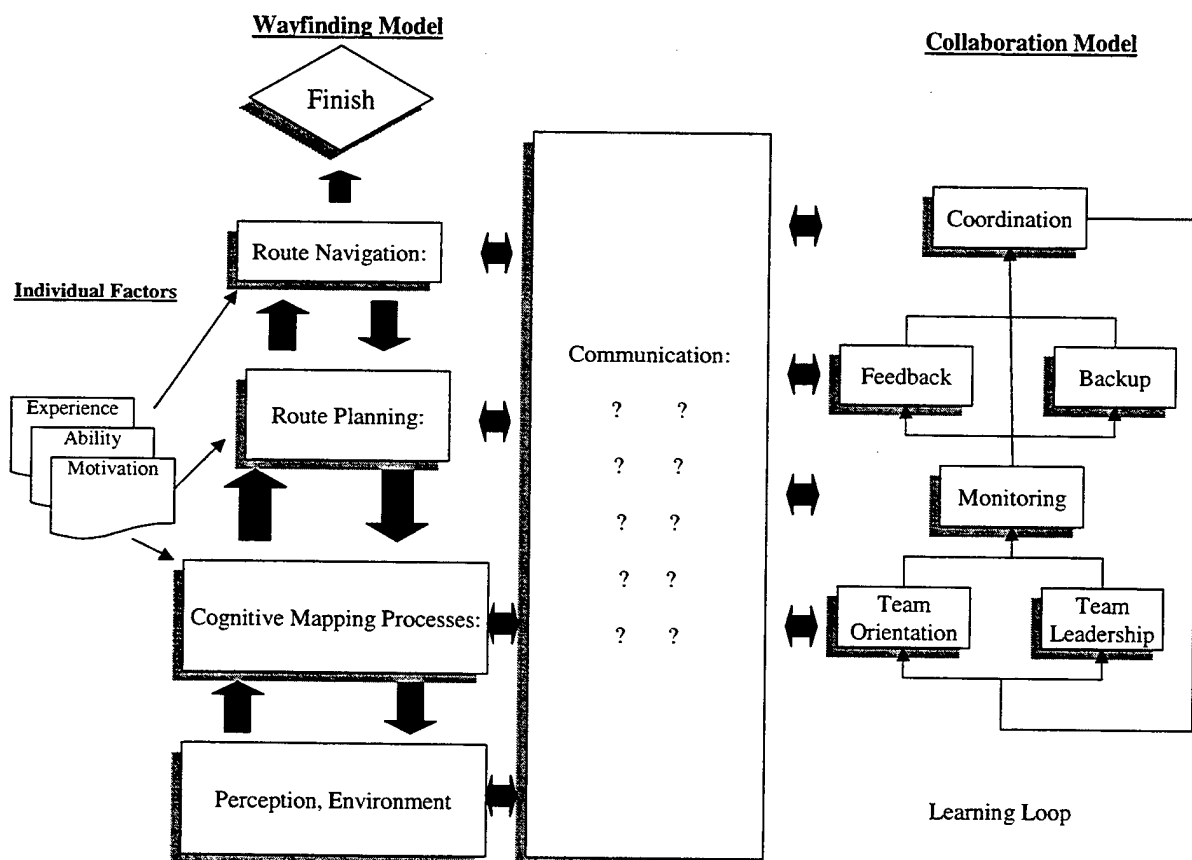
Figure 3.2 Collaborative Wayfinding Model

the accomplishment of wayfinding goals. With this cognitive model as the basis of our understanding of the process, we hope to collect data that either supports the above model or challenges it and thus leads to iterative adaptation. The model or adapted model can

then be used in the design process of a virtual environment intended to support human wayfinding tasks.

C. SUMMARY

We have constructed a theoretical model of collaborative human wayfinding based on the research literature on human wayfinding and on teamwork and collaboration. This model is a rough estimation, at best, of the processes that occur when humans interact to perform wayfinding as a team or collaborative effort. It is not intended or believed to reflect the true nature of human wayfinding, but is our best estimation of the process. That being said, this model is intended to serve as a framework for understanding human interaction in wayfinding, and while not exact, as a framework it provides a basis for understanding and study.

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IV. COLLABORATIVE NAVIGATION FIELD STUDY

A. INTRODUCTION

The purpose of this chapter is to provide a description of our field study and our data collection methods.

B. FIELD STUDY

We developed the field experiment with three goals in mind. First, we wanted to test the validity of our proposed wayfinding model (Figure 3.1) using similar tasks and tests used in previous wayfinding experiments and comparing our results. Our second goal was to examine the general collaboration model, as defined by Dickinson and McIntyre (Figure 2.5), in the collaborative wayfinding arena. Finally, we wanted to collect data on how the collaborative model was supporting wayfinding through communication. How is communication accomplished, what interactions are necessary for effective communication, and how does communication tie together the wayfinding model and the collaboration model? The intention of this study was to test the proposed model of collaborative wayfinding (Figure 3.2), and to provide a rational basis for modification.

1. Implementation

In order to study the collaborative nature of wayfinding we chose a team orienteering task. We decided to re-use the course and tools from a previous wayfinding study (Goerger, 1998), which had examined training transfer between VEs and real world wayfinding tasks. Goerger's study, as described in Chapter Two, provided a solid basis

for our orienteering task, and could provide comparable data if re-focused for a collaborative team study.

a. Subjects

We studied subjects with two distinct levels of wayfinding skill. We studied five pairs of novices and three pairs of experienced land navigators. The first pair studied consisted of novice land-navigators. The subjects were all junior enlisted Army personnel. All of the novice subjects had only basic instruction on the use of a compass and basic map reading skills. They had, as a group, performed only the simplest wayfinding tasks in the field during basic training. They generally described their training as following the compass from one waypoint to the next in a straight line. Previous studies (Banker, 1997; Goerger, 1998; Stine, 2000) have classified this type of wayfinding behavior as novice level.

The second group of subjects consisted of student officers from the Naval Postgraduate School in Monterey, California. These subjects were recruited using a campus-wide email requesting "experienced" volunteers. All of the subjects filled out a short questionnaire (Appendix A) listing their general qualifications as an experienced land navigator. Three of the members of this group had more than ten years of experience in "special forces" activities and could safely be assumed to be expert navigators. The other officers were judged from their questionnaire responses to be in the intermediate to experienced range. These officers had a mix of experience ranging from advanced training (SEALs, Rangers, Special Forces) to Navy Survival Evasion Resistance and Escape (SERE) training, and training with the Boy Scouts of America, to extensive field experience with the U.S. Marine Corps.

b. Tasks

Teams of two personnel, who were either both novices, or both experienced navigators, performed the orienteering task. They were given a short description of the problem (Appendix B) and required to read and sign the required consent forms (Appendix C) during the indoctrination phase. The administrator then read a short mission-planning brief (Appendix D), which described the basic orienteering problem, any restrictions, and introduced all of the planning tools (Appendix E) they would be allowed to use. The indoctrination period lasted about 15 minutes and participants were encouraged to ask any questions they might have. The teams were given 30 minutes to plan the route, they were asked to annotate all of their notes on the 1:5000 map, which would be the only tool used in the field.

The team problem consisted of navigating a short (~3nm) orienteering course over moderate terrain located on former Fort Ord Army Base, California. The course area had varying levels of vegetation, from trails, to run-able forest, to impassable brambles. The team was told to plan on using the compass and map as little as possible between control points and to plan on having a mandatory map and compass check at each control point (this procedure was advised based on experience with previous similar studies). The team was notified in advance that there would be notional "gun emplacements" on the course and that they would be asked to annotate the location of any "gun emplacements" (blue control points).

The orienteering course consisted of nine orange and white control points placed in a manner that would provide increasing navigation difficulty as the team worked its way from the start point to finish point. The area was crisscrossed with small

trails and infrequent jeep tracks and was bounded by an asphalt road and an improved dirt road. There were no major features such as large towers or mountains that might provide a steady heading source. Trees in the area were approximately 25-30 feet high and blocked the horizon from almost any location inside the course area. The only obvious heading source, aside from the compass, was the sun.

The team was required to navigate between control points primarily without the use of the map and compass. If they were unsure of the current location or their next direction of travel they were required to ask for the map and compass. The reasoning for this procedure was two-fold. First, limited use of the map and compass would require the team to build a more complete and accurate mental model of the terrain and course to accomplish their objective. Second, not having the map or compass for reference would encourage collaborative behavior, negotiation and other forms of interaction that would provide valuable information for analysis. We also wanted to perform short interrogations each time the navigation tools were used to examine why the team needed to use them.

The team was advised that the administrator would only correct them if they were off course for more than five minutes or were crossing the out-of-bounds area.

c. Tools

Teams were provided with an overhead photo, a 1:5000 scale orienteering chart, a 1:24000 scale chart, photos of the control points, and an Army lensatic compass (Appendix E). Control point photos were taken using a digital camera, from two angles. This provided the participants with an up to date view of the area of each control point.

The orienteering chart was hand made by Banker (Banker, 1997) for his research project. On this chart the density of vegetation and the layout of the trails was extremely detailed and accurate. Elevation data was incorporated at ten-foot elevation intervals. Our primary reason for using this chart vice a standard military chart was the small scale of the navigation problem.

2. Data Collection

Our methodology in collecting data from this study was driven by the need to examine the model of wayfinding, and to explore the additional aspect of collaboration in wayfinding. Each team began the wayfinding task with a 30 minute planning session, which began as soon as all of the administrative paperwork and introductory briefings had been completed. During the planning session audio and videotape was recorded using a Sony Hi-8 video camera. The administrator observed the planning session and stopped the planning at unscheduled intervals to ask questions designed to gain insight into the cognitive background of certain types of decisions.

a. Wayfinding

We relied on several widely used spatial awareness tests (Bailey, 1994; Witmer, Bailey, & Knerr, 1995; Banker, 1997; Goerger, 1998; Hunt and Waller, 1999) including projective convergence, map reconstruction, and blind (without navigation tools) route performance. The team was monitored using a Garmin GPS III, with location data collected at 30-second intervals as well as audio and video recording. The waypoints from the GPS were later overlaid on a scanned image of the map that the team had planned with and used in the field. The average deviation from the planned route could then be calculated using the distance from the plots to the planned route on the

team map. The administrator of the navigation task was permitted to interact with the subjects for two conditions. If the team strayed off course for more than five minutes and were showing no progress toward the next control point, the administrator would show them the map, the approximate current location and allow them to plan a new route to the next control point. The administrator also instructed the team on their next task at each control point. These tasks were comprised of navigating the next leg of the route and performing a variety of spatial awareness tests.

b. Spatial Awareness Tests

The spatial awareness tests chosen for this experiment were twofold. First, we used a variation on the projective convergence test at three of the control points. The team was given a color coded wheel (Appendix F) and asked to indicate to the best of their ability the heading to three other control points. The variation used here was that the other control points were not the same in each test. This variation meant that the centroid of multiple cuts to a similar target could not be calculated. However accuracy and heading error could be measured and are considered effective indicators of spatial awareness. The teams worked together to accurately locate notional gun emplacements on the map. This test commenced once a team had identified a gun emplacement. The team was then given the map and asked to annotate the location of the emplacement, to the best of their ability, using a code scheme to identify the different gun-points.

c. Applied Cognitive Task Analysis

Cognitive Task Analysis (CTA) was employed with the objective of identifying the cognitive aspects of wayfinding, which need to be directly supported in a virtual environment. After reviewing a variety of methods, which tended to be labor and

40

training intensive, we settled on a simplified cognitive task analysis method designed for use by the layman. Klein Associates developed Applied Cognitive Task Analysis (ACTA) (Militello, Hutton, Pliske, Knight, Klein, and Randel, 1997) for the U.S. Navy as a means of developing course material for Instructional Designers. This methodology provides a set of tools that elicit important cognitive aspects of expert performance, and that are more easily learned than earlier Cognitive Task Analysis methods (Militello, et al., 1997).

After examining the methodology provided by the ACTA tools, we settled on two approaches to our specific problem. First, while ACTA provided tools across the spectrum of knowledge elicitation from the earliest stages of interviewing subject matter experts (SMEs) and learning the basics of the subject, we already had an advanced model of the wayfinding task. This model was based on data collected from a wide variety of experts through observation and interview techniques. We chose a modified version of the "simulation interview" (Militello, et al., 1997) as our method of choice in applying ACTA to our study.

The simulation interview consists of using specific interview techniques to solicit an expert's view of the problem solving process in a specific domain. This interview technique is intended to provide the researcher with specific details of an expert's cognitive processes. This technique involves having the SME read, watch, or interact with a simulation, and interviewing the SME on his reaction. This method is intended to provide the interviewer with a list of critical data about the simulated event. The interview sheet (Appendix F) was used along with the ACTA methodology to guide

an investigation of critical aspects of the team's wayfinding performance. This interview sheet contains a list of the types of data to be collected during the simulation interview.

Our main source of data on collaboration was the process of reviewing the tapes of the team performance. These tapes were reviewed, using the general model (Figure 2.5) as a guideline for data collection, with the goal of collecting information on the methods of interaction used to provide the framework for collaboration in this domain.

V. FIELD STUDY RESULTS

The results from our field study are primarily based on subjective analysis of both modified simulation interviews and video taped performance of wayfinding in the field.

A. COGNITIVE DEMANDS TABLE AND CRITICAL CUES

Our analysis of the data obtained during simulation interviews, which were conducted at the end of the active navigation portion of the experiment, resulted in the compilation of a cognitive demands table. The particular tasks, planning a route, correcting course, identify location when off course, and evaluate progress, were identified based on the criteria from critical decision incident theory (Klein, Calderwood, & MacGregor, 1989). The complete cognitive demands table below (Table 5.1), lists the four tasks and the fused input from the various team members.

The tasks focused on during interviews conducted at the completion of the simulation were: Planning a Route, Evaluate Progress, Correct Course, and Identify Location When Off Course. These tasks were chosen because of the impact they had in terms of accuracy and orientation on wayfinding performance.

1. Critical Cues

The list of critical cues gleaned from interviewing the participants, and contained in the cognitive demands table, provide valuable insight into the source of many of the decisions made in the field. The two most commonly noted cues used by the experienced navigators were terrain association and pace count. These cues were mentioned in almost every critical incident debrief as playing an important role in the

43

final decision. The experienced navigators combined these cues with other lesser cues, such as trail intersections, manmade objects, time, and vegetation patterns to make their decisions.

What is the difficult Cognitive Element?	Why is it difficult?	What steps does an experienced navigator use?	Critical Cues	What strategies are considered?	What errors might a novice make?
Planning a route.	Have to compare alternatives. Need to be able to visualize terrain. Must recognize limitations of the map, real world is always more confusing. Trails clearly marked on a map might be obscured or invisible. Finding a specific trail is much harder than finding a specific road.	Identify easily recognizable features. Identify straight course to objectives. Choose a path that utilizes most recognizable features such as trails, roads, ridgelines or other landmarks. Memorize terrain features and course and pace count information. Utilize sand box or other 3 dimensional tool to visualize terrain.	Changes in terrain elevation. Trail intersections. Ridgelines. Roads. Catching feature. (generally some obvious terrain feature, or man-made feature that can be offset to)	Use intentional offsets to a catching feature. This way the navigator knows which direction to head once a catching feature is found. Only use roads or paths in low threat arena. In high threat or enemy territory, use offset from ridgelines or roads. Strategy based on mission and threat.	Attempt to follow a direct path based only on heading. Hard because, terrain may not accommodate and if your heading is off, when you recognize this, which way are you off-left or right? Choosing poor landmarks, such as small trails or terrain features not identifiable.
Correcting Course	Recognizing that you are off course. Requires strict comparison of original expectations to environment. Recognizing that you have missed the control point. Know general location, just hard to find control point. If no catching features or plan is based only on pace count and heading.	Rely on pace count. Use easily recognizable catching features. Identify location. (GPS) Plan new route based on current location or retrace steps and try again.	Pace Count. Terrain association. Time. Catching features. Understanding difficulty prior to performance. (expecting a particular part of the route to be difficult)	GPS. Intentionally deviate from plan to gather information Return to known point, repeat pace count. Pick a control object and walk concentric circles. (other similar methods)	Losing point of reference. Not retracing to known point. Not accurately identifying location. Not using terrain association. Not recognizing differences between expected terrain and landmarks and actual. Moving beyond ability to backtrack. Inaccurate pace count.

44

What is the difficult Cognitive Element?	Why is it difficult?	What steps does an experienced navigator use?	Critical Cues	What strategies are considered?	What errors might a novice make?
Identify location when off course.	Unfamiliar terrain. Limited landmarks.	GPS. Identify local landmarks features. Examine local terrain features such as elevation, trails, or other features. Compare to map. Consider movements since last known location. Consider backtracking.	Terrain association. Pace Count. Trail patterns. Any obvious landmarks such as buildings, roads, telephone or powerlines.	Consider backtracking. Use GPS. Identify new location and re-plan route	Incorrectly identify location. Not backtracking to a known location. Continuing movement beyond ability to backtrack.
Evaluate Progress	Must compare terrain features to memory. Matching preconceived picture to real picture. Scale mismatch. Extra detail in real terrain can confuse memorized details.	Evaluate last known location. Compare local cues to expected cues. Dismiss poor cues. If progress is understood, proceed, else backtrack or replan route.	Terrain association. Pace Count. Any obvious landmarks such as buildings, roads, telephone or powerlines. Trail patterns. Time. Vegetation density. (based on 1:5000 Map)	Re-examine map. Backtrack to known location. Test evaluation, look for expected cues further on route. Gather more information, circling search or direct inquiry.	Not recognizing the need to evaluate. Mismatching cues from environment to the mental representations. Using poor cues from terrain. Loosing track of time. Not backtracking.

Table 5.1 Cognitive Demands Table

This finding is supported by other studies of expert navigators (Stine, 2000) in which "blending of multiple cues" is noted as a distinguishing feature of expert performance.

Terrain association was used both consciously and unconsciously. In the field the teams were noted comparing the features in the terrain directly to the map as a source of cue integration and self-location. This behavior was deliberate and directed at identifying nearby terrain features to aid in the decision making process. They were also noted using terrain features unconsciously. This behavior was used in relation to the largest terrain features in the vicinity of our study, namely, a large ridgeline that bordered the south edge of the area and a large depression in the center of the area. We identify this

behavior as unconscious because during debrief, and only after being specifically questioned about the cues used, did subjects realize what cue they were using as a general frame of reference.

2. Cognitive Challenges

Our data indicated a strong reliance on the ability to develop a three-dimensional visualization of the terrain and to continuously correlate between real and expected cues. The experienced navigators based many decisions, both in the planning phase and in the execution, on terrain association. Visualizing three-dimensional terrain was identified as a cognitively difficult skill. Experts recommended using a sandbox or some other three-dimensional mockup of the terrain to help develop an accurate visualization.

The experienced navigators also discussed the difficulty of developing a realistic overall expectation from the two-dimensional tools provided in the planning session. The tendency for novices was to have unrealistic expectations at the beginning of the route. Many of the novice groups used words like "easy" to describe the first leg of the route, and all of these groups got lost on this leg. Their mental expectation was poorly formed and they generally overestimated their wayfinding ability. The novice ability to correlate cues from the environment to their mental map was particularly poor at the beginning of the route. The experts had well formed expectations and correlated cues efficiently. This allowed them to continuously update their mental map as they moved through the environment.

Recognizing the dissonance between real world cues and cognitive expectations is a particularly challenging aspect of land navigation. The expert teams discussed a loose expectation, which was adjusted often to match the environment. Novices on the other

hand developed "hard" expectations or had very poorly developed expectations. That is, they seemed to have a picture in mind that had to match before they would recognize it or no organized expectation at all. This behavior was often displayed when the novices strayed from their planned course. The required cues were available but did not meet fairly strict selection criteria chosen by the novices. The experienced navigators emphasized the importance of having loose expectations and looking for multiple cues. They use multiple cues based on experience; if you have only one cue to look for then you only need one mistake to end up off course.

3. Expert Strategies

The experienced teams used and discussed several strategies, which they considered critical to success in land navigation.

The teams relied heavily on catching features in the terrain. This type of behavior is identified (Goerger, 1999) as "coarse navigation." A catching feature is one that is easily identified and unlikely to be missed during navigation. This type of feature is not the goal of the navigation effort but is generally on the correct heading, easily identifiable and usually linear such as a tree line, a road, or a trail. Once a catching feature is recognized, the navigator has an expectation of his location relative to the goal. This type of navigation was also referred to as "aiming off" because the plan would intentionally offset left or right of the goal in order to use a catching feature.

The use of a catching feature as an "attack point" is another strategy used as the basis of "fine navigation" (Goerger, 1999). This strategy involved choosing a catching feature that was near the goal (control point or final goal) and developing a route plan based on finding the attack point and then navigating to the goal.

47

Intentionally deviating to use terrain features and landmarks that could be readily identified was also a strategy commonly used by the expert teams. When routes were compared or discussed during the exercise the experts generally recognized that the expense of deviating, in terms of time and energy, was more than worth the effort. They based this strategy largely on past experience. A direct route that has poor catching features or limited landmarks available may end up taking more effort and being more difficult than one that intentionally deviates.

When a team's present location was in question, a common strategy was to backtrack to the last known location and either reevaluate the position or the plan. Novice teams did not use backtracking and often proceeded beyond their ability to do so. The expert teams used backtracking when necessary and indicated that their ability to backtrack was a consideration when making decisions about location and movement. They intentionally limited their movements based on the ability to backtrack.

B. RECOGNITION PRIMED DECISION MODEL

In analyzing the performance of the individual teams we looked for a pattern of communication. That is, we studied each team as they discussed the problem at hand, looking for an identifiable pattern of communication that could lend insight to the team coordination aspect of the wayfinding task. At first, no discernable pattern emerged from the data. Interaction seemed to vary according to personality and skill level and did not have similar characteristics across the groups. As more groups completed the study and their performance was analyzed, a pattern emerged. The groups seemed to follow a general pattern in working together to solve the wayfinding tasks.

1. Planning

Every group took advantage of the mandatory map and compass check at each waypoint to orient themselves to the terrain, discuss the specifics of navigating to the next point and agreeing on the next course of action. The amount of detail included in these "orientations" varied according to skill level.

The novice navigators generally oriented themselves by reviewing the distance and heading to the next control point. The level of detail in novice orientation improved considerably after the first control point was reached. All of the novice groups ended up disoriented or lost on the first leg of the route. The problems encountered early on the route by the novice groups may have accounted for their steep learning curve. Novice performance improved dramatically after the first waypoint was reached. We believe that this was accounted for by several variables. First, the scale of the map (1:5000) was of such detail that all of the novice navigators initially overestimated distances. Even though all of the teams measured the distances between waypoints correctly on the map and most of them discussed the proper pace count, this did not translate into a physical understanding of the distance. After experiencing the terrain and comparing features in the terrain to the map on the first leg of the route, the novice teams in general had a much more accurate sense of scale in comparing the map to the terrain. This variable (scale interpretation) was identified from the performance in the field and verified in debrief interviews as playing a significant part in the initial poor performance of the novice groups as well as one of the experienced groups. Another variable was attention to detail. After getting lost once the novices paid considerable attention to the details in the terrain

and the detailed information available on the wayfinding map. They also requested map and compass checks much more frequently after the first leg of the route.

Novice performance of orientation improved after the first leg of the route. They carefully oriented the map using the compass and then identified landmarks in the terrain that compared to and could be identified on the map. After this step, the novices more carefully discussed and memorized any information they needed to navigate to the next control point, such as trail intersections, vegetation, buildings, power lines, distance, heading. Several of the groups used a straight-line method of navigating. This method consisted of one member standing still and guiding the other member as he walked in the direction of the next control point. In this manner, the team could leapfrog along and keep their heading accurate. Another method was just to use two landmarks, such as trees or buildings in line and navigate along the line of those landmarks.

The experienced teams spent considerably more time discussing details and reviewing salient landmarks and measurements before beginning the navigation problem. This difference is indicative of the experienced teams establishing a well-framed cognitive understanding of the problem prior to starting the navigation task. The experienced teams generally identified more realistic landmarks to guide their navigation. They also identified landmarks that were unlikely to be obscured or to blend in with other landmarks on the course. In contrast novices assumed they would be able to tell one trail from another and that they could identify the different levels of vegetation based on the map. Whereas the experienced teams generally relied on changes in terrain elevation, trail intersections, or other easily identifiable features. Another feature of experienced

team "orientation" was careful orientation to the map and careful identification of local observable landmarks before discussing the next leg.

2. Story Processes

As the teams progressed through the course, they would stop at intervals to discuss their progress and plan the route to the next control point. The discussion and decisions made at these points significantly affected the outcome of the team's performance, and they were identified as Critical Decision Incidents (CDI) (Klein, Calderwood, & MacGregor, 1989). These researchers describe CDIs as those that can illustrate non-routine aspects of a domain. In this case, incidents were chosen that met three criteria: the incident clearly affected the outcome of the navigation task, the team spent a significant amount of time and effort to make a decision, and the problem appeared to the administrator to be cognitively demanding. The last criterion was purely subjective and was left to the administrator's experience and judgment.

We used an interview method based on the critical incident method (Klein, Calderwood, & MacGregor, 1989), and the simulation interview method from Applied Cognitive Task Analysis (ACTA) (Militello, et al., 1997). This method was modified to support the investigation of more limited incidents. We used the simulation portion of the ACTA protocol and concentrated the interview on actual vice simulated performance. The method was particularly effective at eliciting cues, goals, options, and other aspects of a critical incident as identified by Klein, Calderwood, & MacGregor (1989).

Analysis of these incidents led to the observation of a pattern of interaction between the team members. This pattern consisted of distinct steps in solving the wayfinding problem and was utilized by both the novice and experienced subject groups.

51

The teams began the pattern by studying the tools provided and planning their route through the course during the briefing session. This part of the pattern was identified as "story generation" and we label it this way to tie it in with other aspects of problem solving. Story generation consists of developing lists of goals, expectations, and cues, which are intended to guide the team through the performance of an expected task. In this case, the team members generate their story while performing the brief/study aspect of this task. They review the materials, generate a course of action, and identify what they believe will be salient clues and cues in achieving their goals. This aspect of team performance is normally identified as team experience (Stout, et al., 1999) and generally is tied to shared experience and practice in a known environment. In this case, the environment and the team were unfamiliar to the participants and story generation consisted of a very short planning interval and continued throughout the experiment. The limited experience these team members had with each other is important, since advanced modes of team operation, such as backup or implicit coordination, typically emerge only with groups that have spent more time training or working together (Cannon-Bowers, Salas, & Converse, 1993).

Recognition primed decision (RPD) theory (Klein, et al., 1989) (Figure 5.1) recognized that decision-making consisted of three general levels. The first was "simple match," which is identified as a situation that is recognized and "the goals are obvious, the critical cues are known, expectations about future states are known and a typical course of action is recognized" (Klein, et al., 1989). The third level was identified as "evaluate an action." This more complicated function consists of deliberately assessing a

course of action by running mental simulations and modifying the plan until a reasonable
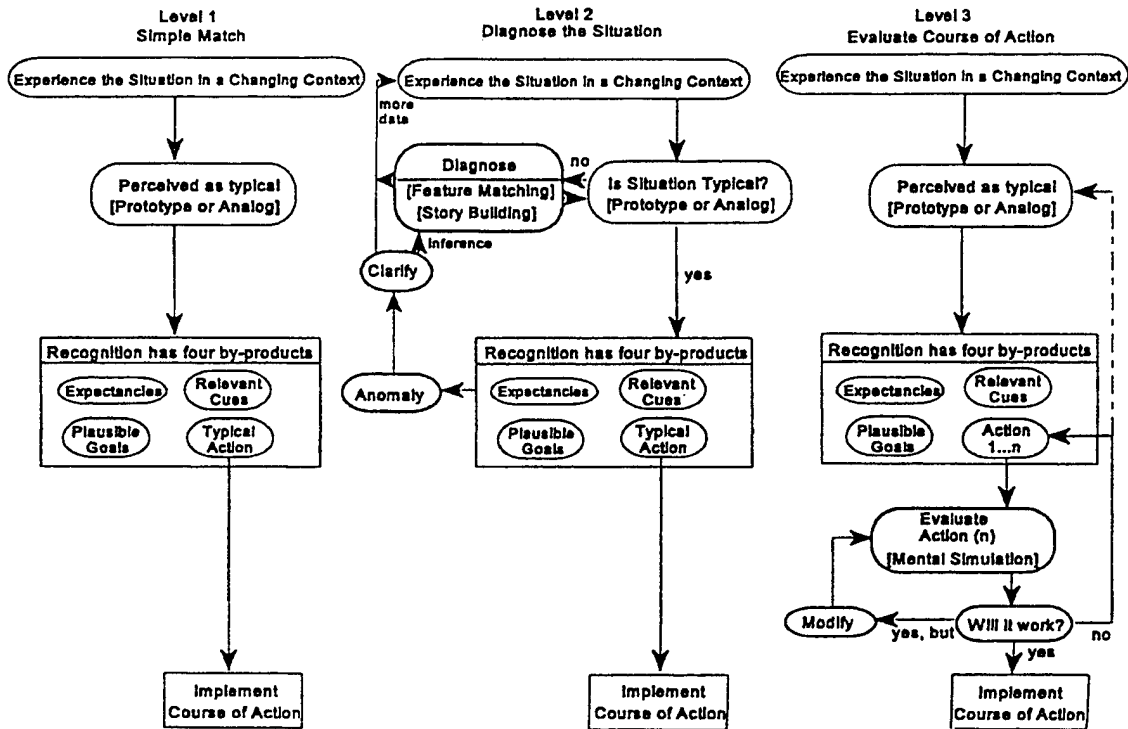
course of

Figure 5.1 Recognition Primed Decision Model (From: Klein, et al., 1989)

action is decided on. The recognition primed decision model seems to fit the pattern of

team interaction and decision making identified in the field study. The teams would

navigate using the original story, which had been mutually generated, until it violated the

cues from the environment. Once the difference between the environment and the

generated story was recognized, the teams began retelling the story to include the new

information (Figure 5.2). This pattern is identified in the RPD model for individual

decision-making and fits the behavior of the wayfinding teams performing collaborative

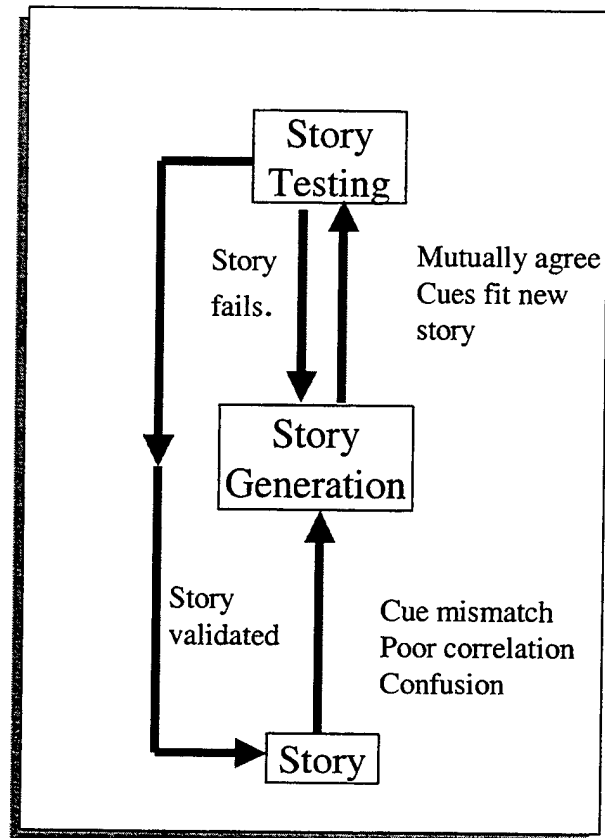decision-making. The pattern (Figure 5.2) generated from our analysis

Figure 5.2 Story Processes

of the interaction of team wayfinders directly matches the RPD model (Figure 5.1).

Upon further review the RPD model was observed to fit well with the decision-making

behavior we observed during the planning sessions of the experienced groups. The

experienced groups generated route options during planning, verbally simulated the

options, and then agreed to discard or utilize the option. This process also closely

resembles the RPD model lending further evidence that RPD has validity for the

collaborative wayfinding process.

3. Story Generation

The second part of the pattern consisted of attempts by team members to individually explain or evaluate the environment as it related to the original story. We have labeled this aspect "story generation" since it consisted of extending or revising the original story. This part of the pattern emerged whenever teams encountered aspects of the environment that did not fit or did not support their original story. Team members did not always agree on the circumstances of the situation. Often only one subject would feel that the team was significantly off course or that the expectations of the environment did not match the model adequately enough to continue. In this situation the teams defaulted to story generation to discuss the situation. Story generation consisted of relating various aspects of the experience, such as specific landmarks or terrain elevation cues, to the mental map and the original plan or story. Each member of the team would propose a story to explain the specifics of the situation. Sometimes the team members would propose opposing view points, sometimes the second team member would repeat the story proposed by the first team member with minor modifications. This process continued until the team had agreed on a story or decided to test a story.

4. Story Testing

Testing of a proposed story was the final aspect of the pattern of interaction. This process consisted of accepting a proposed story and proceeding with the navigation problem as if the accepted story was accurate. During the test aspect, the team members collected data while following the proposed story to either verify or dispel its validity. Once a story was validated the process continues in navigation mode. If a story is invalidated the process reverts to the story generation level.

C. LOCOMOTIVE INTERACTION

An accurate pace count was stressed throughout the study as vital to establishing an objective understanding of distance traveled. During the debrief session experienced groups repeatedly noted that inaccuracies in pace count can have a pronounced effect on land navigation problems. Subjects also directly referenced the "feel" of terrain as an important factor in distance judgment. The feel of tilted terrain is considerably different from straight and level terrain. This data raises questions about the importance of the sound of footsteps and the feel of friction from the ground surface in an experienced navigators ability to judge locomotive information. For wayfinding, locomotion is a critical aspect of interaction and cognition when making decisions based on distance traveled.

We hypothesize that a Collaborative Virtual Environment (CVE) designed to support training or simulation of wayfinding will need to support locomotive interaction as a means of accurate distance estimation. Without this basic interactive feature the user will likely find it quite difficult to estimate distance traveled during navigation. If another means of distance estimation is provided then a basic task in wayfinding will be left out during the simulation. We believe that providing a modified method of estimating distance traveled will, in this case, provide a negative training effect and should be avoided.

D. INTERPERSONAL COMMUNICATION

Several aspects of interpersonal communication played important roles in team decision-making and collaboration. This interpersonal aspect of collaboration may be

especially relevant when discussing the design of collaborative virtual environments because human interplay and communication forms the basis of team decision-making. This may seem like an obvious statement, nevertheless, it is an important one. Without communication there is no team and no collaboration. So what are humans engaged in team wayfinding using to communicate? Fully and completely answering this question would require study and skills that are beyond the scope of this study. However, several modes of interaction seemed to be critical to interpersonal communication and the decision-making process. While verbal interaction is an obvious important mode of communication there are other aspects that have considerable impact. Without going into technical depth, which is beyond the ability of the author, we attempt to describe some of the most obvious aspects of this interaction.

1. Visual Affirmation

Visual affirmation is our layman's attempt to describe a process used across the spectrum of skill levels. In the process of story generation, team members spent considerable time studying their partner's face. This process seemed to play an important role in choosing which story to test. In fact, it was noted that the team member who seemed to have more conviction when telling his story sometimes carried the decision point, even when the facts matched very poorly with the proposed story. This mode of interaction possibly represents a typical mode of human interaction in which one person gauges the other's conviction based on cues displayed through human body language. Exactly what these cues are and how they can be categorized is beyond the scope of this investigation. But we recognize that body language and facial emotions play an important role in mediating team decisions in a face-to-face environment and in particular

the collaborative wayfinding environment. We feel it is important to note this interplay for possible future study. This interplay, or the lack of it, may affect training transfer when using CVEs to train or practice team land navigation tasks.

2. Peripheral Interaction

Studying the interaction of the teams in the field identified this aspect of interaction. Team members appeared to be able to indicate landmarks or share information without directly facing or focusing on one another. Pointing by hand for instance was initiated and acknowledged without apparent direct attention. Peripheral interaction seemed to play an important role in the team member's ability to shift the focus of the partner and to communicate while on the move. Peripheral interaction was used extensively while communicating about the environment and the correlation of the environment to the story being used.

3. Gaze Tracking

Gaze tracking was another mode of interaction that played a role in pointing and landmark or cue indication. Subjects were noted using the eyes of their partners as a guide to particular points of interest throughout the exercise. This may be another implicit mode of interaction like visual affirmation.

4. Personality Traits

During the planning phase, the teams exhibited what we labeled "testing" behavior. At the beginning of the planning phase, after the inbrief was complete, one of the subjects initiated some general discussion about how to accomplish the task. This was followed by a series of give and take questions. This is just one example of

personality interplay that was important throughout the study. There were several instances during the study in which the "leader" led the team off course when the "follower" seemed to have better spatial knowledge and situational awareness. Is this type of interaction reproducible in a virtual environment? Will a lack of personality traits such as physical bearing, voice modulation, or any of a number of other physical or psychological cues change the way individuals interact in a virtual environment? These questions are important to the design of collaborative virtual environments and deserve further study.

E. SUMMARY

Our analysis of the wayfinding process through cognitive task analysis and through observation of wayfinding in the field has provided valuable subjective data. The data in the cognitive demands table provide insight into the cognitive processes used by expert navigators and the cues that they use. Exploration of the relationship between the cognitive processes used during collaborative wayfinding and the recognition primed decision-making model may provide valuable insight into methods to be used for further investigation. The importance of proprioception to the expert land navigator provides a distinct challenge to the developers of virtual environments. Finally, the aspects of interpersonal interaction noted provide a broad avenue for further research. The importance this interaction has for training, augmenting, or practicing collaborative wayfinding cannot, at this time, be quantified, however, based on our observations, it has a distinct role in the collaborative wayfinding task and requires further investigation.

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VI. CONCLUSIONS AND RECOMMENDATIONS

A. DISCUSSION

Our original hypothesis was that a detailed cognitive model of collaborative interactive activity could be used as the basis for design of a collaborative virtual environment. We focused our research on human wayfinding in natural terrain and on the collaborative aspects of human interaction to develop a model of collaborative human wayfinding. Novice and experienced land navigators performed a cognitively challenging wayfinding problem as a means of testing the proposed model in the field.

Our study was designed to examine the validity of the wayfinding model and to develop an understanding of the collaborative aspects of wayfinding as a team. Applied Cognitive Task Analysis (ACTA) was used to elicit cognitive data on the wayfinding process and modify the collaborative wayfinding model. ACTA proved invaluable for structuring the interview process and providing a framework for cognitive task analysis.

The methods we used have proven value based on the information collected and the relevance of this information to the design aspects of collaborative virtual environments. We do not, however, believe that our method is comprehensive. There are aspects of interpersonal communication that do not lend themselves to interpretation through cognitive analysis. Other study methods, such as behavioral task analysis should be investigated in order to develop a more comprehensive method of accurately modeling collaborative requirements.

Our analysis of team interaction revealed an unexpected correlation with Recognition Primed Decision-making theory. Our research was focused on

61

understanding the communication factors involved in team wayfinding and those turned out to fit the general model of Recognition Primed Decision (RPD) theory.

1. User-Centered Design

This study utilized user-centered design principles to model a specific activity in order to provide the basis for designing a collaborative virtual environment. This process has resulted in improved understanding of the cognitive processes required for human collaborative wayfinding. The cognitive model has direct application for a designer ranging from interface development to model design. Information critical to design such as critical cue libraries for certain cognitively challenging decisions is available through our methods. A critical cue library, for example, can provide a rational basis for the detail level needed in a terrain model used for collaborative virtual wayfinding.

The cognitive modeling process also provides valuable insight for interface development. Whether a project has the goal of training or augmenting a specific task, cognitive modeling presents a method of eliciting understanding of the cognitive processes required. This data can then be used to develop interfaces to support the cognitive demands of specific tasks or to establish the criteria for model development.

2. Modified Model of Collaborative Wayfinding

We began our study with three goals in mind: validating the wayfinding model, examining the collaboration aspect of wayfinding, and developing a collaborative wayfinding model.

The proposed layering of the major aspects of wayfinding (Environment, Cognitive Mapping, Route Planning, and Route Navigation) is supported by our data.

Team member interaction with other members, and the environment, provided direct corroboration of the wayfinding model described previously in Chapter Four. The differences noted between the behavior of the novice and experienced navigators in our study correlate with the distinct processes described in our model. Novices developed poor cognitive maps, made poor choices in route planning, and had difficulty correlating multiple cues from the environment. Experts on the other hand excelled in all of these distinct areas.

The data contained in the cognitive demands table (Table 5.1) also lend support to our model. The cognitively challenging aspects identified by the behavior and decisions of the experts fit almost directly with the processes described in our model. This correlation lends strong support to the model's general framework.

The communication aspect of this model (Figure 6.1) plays the role of facilitating collaboration. The Story directly supports team orientation and leadership aspects of team wayfinding. This process provides the basis for goal development, shared mental model development (SMMs), task orientation and other aspects of team orientation. It serves as the basis of team leadership by providing a structure against which the actions of the team are balanced. It also provides the architecture for planning and organizing the behavior of the team.

The story generation process is included in our modified version of the collaborative wayfinding model (Figure 6.2). This process serves as the connection between wayfinding and collaboration, namely communication.

Story generation supports the collaborative aspects of route planning and route navigation. During the planning phase, the navigators begin generating stories

(conducting mental simulations) about how they plan to solve the task. This process continues until a story is agreed upon. As they navigate the route, story generation is the method used to interpret the environment and share interpretations with the team.
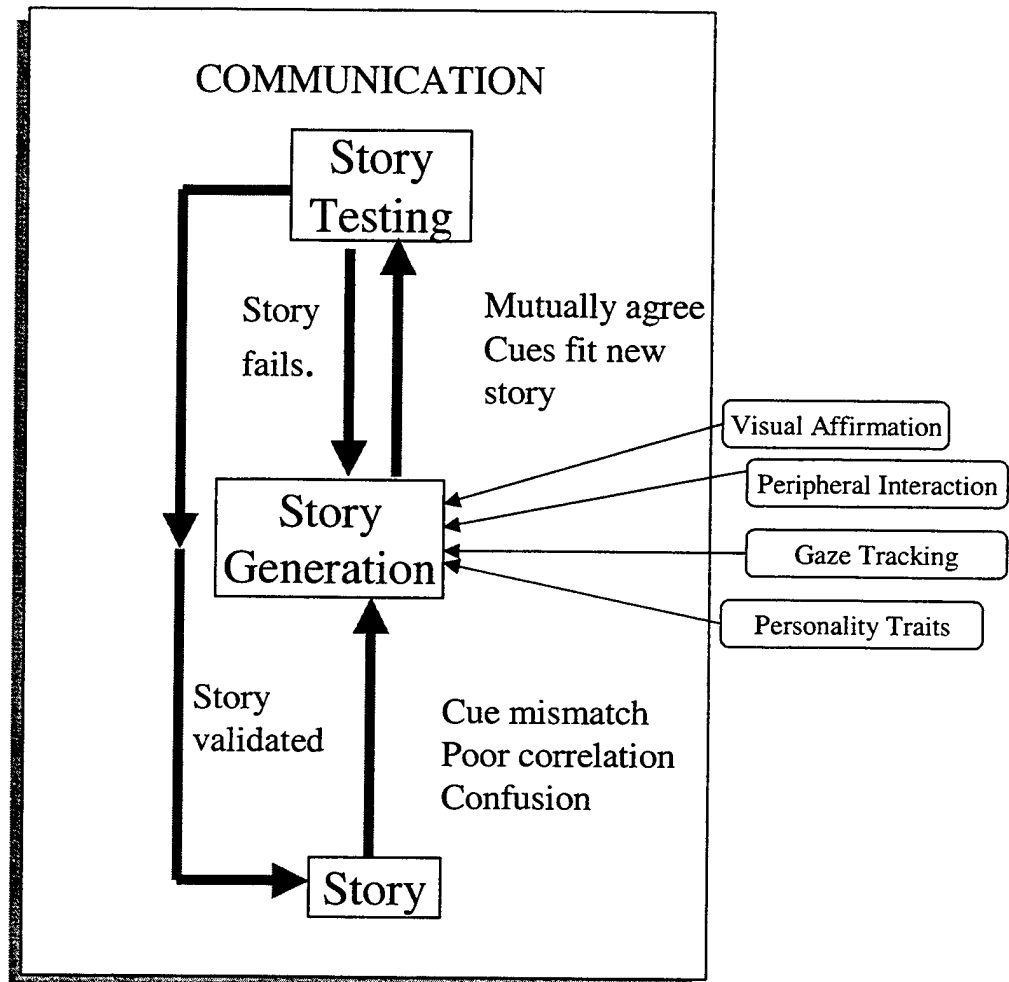

Figure 6.1 Story Telling in Collaboration

Finally, when cues in the environment no longer fit the story, the team generates a new story as a method of understanding the cues presented. This process supports the monitoring, feedback, and coordination aspects of collaboration.

64

Coordination, monitoring, and backup support the route navigation aspect of the model through story testing. Story testing behavior provides the basis for incorporating a new understanding or changing situational assessments and leads the process back to the use of a story as the shared mental model of the team.
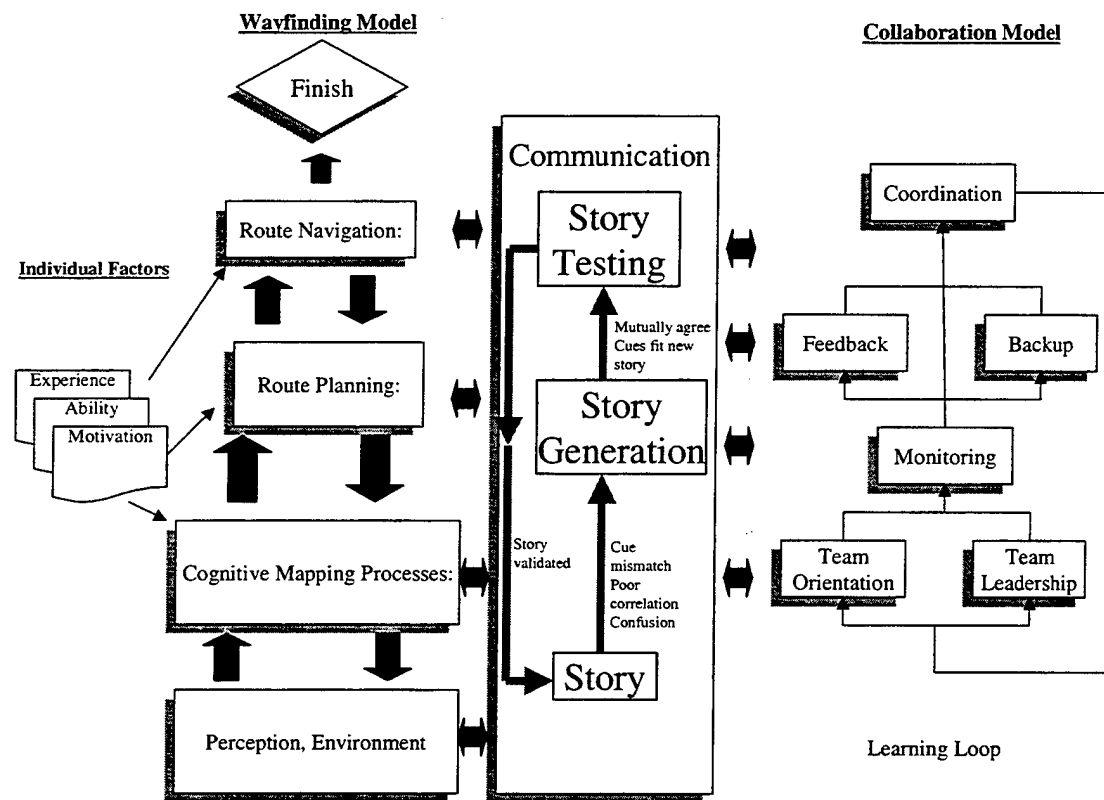

Figure 6.2 Modified Model of Collaborative Wayfinding

B. RECOMMENDATIONS

1. Model and Interface Design

We began this study with the goal of providing the basis for the design of a collaborative virtual environment that would support collaborative wayfinding. Our

study has provided some of the information necessary for that development. The critical cues listed in the cognitive demands table (Table 5.1) are a valuable resource for developing a terrain model. The cognitive demands table also provides a useful tool for developing interfaces that support the cognitive demands of wayfinding. Augmentation is another area where cognitive task analysis might reap benefits. Design guidelines related to human-system interface design and model development in support of collaborative wayfinding are listed in table 6.1.

Interface Guidelines	Model Guidelines
• Sharable navigation tools (compass, map, gps) • Movable navigation tools (rotatable, alignment of the map with the environment is an important orientation action) • High quality voice required (the nuances of voice inflection are important for story judgment) • Implement some form of shared visual pointing (this supports story sharing, what is being discussed, where is it in the environment, etc) • Gaze tracking is a very difficult problem, but perhaps a workaround like a flashlight or spray paint tool would suffice for a similar purpose • Personality traits are an important aspect of interaction in wayfinding. Any interface element which helps to share personality should be considered for this type of VE • Realistic, synthetic locomotion	• Accurate high detail elevation modeling • Linear catching features (tree lines, trails, roads, telephone lines, streams) • Catching features that are referenced on the map. • Orientation features, identifiable discrete elements are very important if proprioception is not available • Provide multiple cues throughout the model. Experts evaluate multiple cues, such as elevation, trail intersections and foliage patterns. • Support Thorndykes (Figure 2.1) model of spatial awareness. Provide landmarks, linear route connections, and survey elements to support the development of spatial awareness.

Table 6.1 Wayfinding Design Guidelines

Our interview data indicates a strong requirement to include locomotive devices in a collaborative virtual wayfinding environment. Locomotion is the primary method military wayfinders use to gauge distance and to correlate environmental cues to their cognitive mental map. Thus, we believe unnatural methods of motion in a land navigation trainer would provide negative training value.

While aspects of interpersonal interaction used by team members to communicate requires much further study, our perception is that it is a critical aspect of the collaboration process and thus critical to valid decision-making.

2. Study Methodology

We developed our study with the intention of using Applied Cognitive Task Analysis techniques to develop a comprehensive model of human collaborative wayfinding. While this method proved invaluable in our study, it is not directly supportive of the study of collaborative activity. It does not provide interview techniques that directly support elicitation of information from a small group. We noted that during our interviews, which were conducted with two subjects simultaneously, the subjects continued to interact. This interaction may have altered the answers to some questions. Thoughtful and honest evaluation of the question was probably limited due to this method of interview. Other methods may prove more useful in this capacity.

Observation of subjects in the field relied on the use of a Garmin III GPS unit, a Sony 8mm video camera, and a mini-recorder worn by one of the subjects. The camera was attached to a helmet worn by the administrator. There were several difficulties encountered in this methodology. Camera use was less than optimal due to the difficulty of simultaneously controlling the camera and taking notes. Often critical aspects of

interaction or performance were obscured by poor camera use. We would recommend the use of some other method that allows hands free tracking of subjects.

We would recommend utilizing two or more administrators in any future similar studies. This would facilitate sharing of the many data collection requirements (e.g., video, note taking, etc) and allow for more accurate video work and more accurate note taking. Using mini-cameras worn by the subjects might be another option for the camera work.

While the Garmin GPS III performed admirably, we noted that the average estimated error on our device was 20 feet. This accuracy sufficed for our work. Future researchers should consider possibilities for increased accuracy.

3. Conclusions

Our method represents an attempt to apply cognitive science to collaborative virtual environments in much the same manner it has been used effectively in designing other types of computer interface paradigms. Much work remains in order to completely validate the model and to provide other scientifically sound and thorough methods for design of a collaborative virtual environment.

We have noted that some of the interaction recognized as important to the process of wayfinding was beyond the scope of our study. What value, if any, behavioral studies or behavioral task analysis may have to the design process is not known. A clear understanding of the impact interpersonal interactions have on certain types of tasks may prove essential to developing tools that train or augment those tasks.

The implementation of a collaborative virtual environment designed explicitly to train or augment wayfinding remains. Our original goal was to accomplish this task. However, our research generated design aspects that we were not prepared to implement and this goal was set aside. We believe a CVE that implements a natural locomotive interface as well as one that provides for interpersonal interaction would provide the beginnings of a credible collaborative wayfinding environment.

We concentrated our efforts on studying teams of novices and experts performing a wayfinding task. A CVE intended to support the training of land navigation would benefit greatly from a similar study of experts training novices in the field. ACTA was developed to aid instructional developers in extracting expert knowledge for use in compiling training tools. Our experience with the method leads us to believe it would prove useful in future studies aimed at developing and enhancing cognitive models of land navigation instruction.

4. Future Work

This study provides a methodology that successfully elicits cognitive information useful for the use of a CVE. Many aspects of CVE design still require extensive research including:

- What additional data need to be collected to represent a comprehensive model of wayfinding?

- Would use of a larger sample size produce additional cognitive demands not uncovered thus far?

- Does a CVE developed using the guidelines in Table 6.1 provide a more effective tool than one that is not?

- Leadership– How does interface design affect normal leadership roles? Do different levels of immersive quality affect leadership style?

- Mentoring/Training – What can cognitive task analysis tell us about the mentoring task arena. What cues are used, what are the critical goals?

- What is different about wayfinding in other terrain types (thick jungle, desert, urban areas)?

- Can this method be generalized for other task arenas?

APPENDIX A. LAND NAVIGATION QUESTIONNAIRE

Name:_____   Age:_____

Sex:_____

Branch of Service:_____   Rank:_____

    1. Have you had any experience with land navigation?   Y   N

2. If so, where did you first learn land navigation?

    a. Scouting, Boys/Girls club
    b. Parents
    c. Friend
    d. Basic Training
    e. Other_____

3. How many years have you been Oreinteering/Navigating?
    a. Less than a year
    b. One year or more
    c. Two years or more
    d. Five years or more
    e. Ten years or more

4. At what level would you classify your navigating abilities?
    a. Novice/Beginner
    b. Intermediate/Average
    c. Expert/Advance

5. How many time have you land navigated or spent time orienteering in the last year?

_____

    6. The land navigation course runs through varying degrees of vegetation and over rolling terrain. It will require you to negotiate a distance of no more than three miles in one hour. Do you have any physical disabilities that would prevent you from executing this task? Yes/No

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APPENDIX B. PARTICIPANT TASK LIST

Thank you for participating in this study. You will be performing a team orienteering task. Please read the following orientation carefully and feel free to ask questions to clarify any parts of the experiment.

1. You will each be wearing a light pack with DGPS to collect data on your location for post exercise review.

2. Before you run the course you will work together to carefully plan your route through the course.

3. Use this time to commit the route and obstacles to memory. You are expected to do the following on the course:

    a. Work as a team to navigate the course in 60 minutes or less.
    b. Utilize the Map and Compass (Mandatory at each waypoint) only when necessary.
    c. "Think out loud", you are encouraged to explain your decision process, discuss the factors influencing your decisions and cooperate to achieve the objectives of the course.
    d. Attempt to find all of the controls utilizing your planned route.

Course Objectives

1. Navigate on your planned route. (Route errors cost 15 Points)

2. Locate and avoid all notional gun emplacements. (Ambush is 25 Points)

3. Minimize use of the map and compass. (Map check costs 10 points)

4. Maximize teamwork

If you need to check the map, ask the administrator. You will be given as much time as needed to discuss your location and adjust your plan. The administrator will ask you a series of questions before and after each map check. You start the course with 200 points. Points are deducted based on your performance on the course.

If you need to change your planned route, notify the administrator and he will ask you a series of questions and give you a blue pen to perform the changes.

Map Marking

You will use a red marker to annotate your initial navigation plan. All changes will be made with a blue marker.

You are allowed to deviate from your planned route within the following tolerances while still being considered on that route:

Jeep Trails, Paved Roads, Unpaved Roads, Indistinct Paths, Narrow Rides and Paths – if your marked route is on any of these features you are allowed **3 meters to either side** of the feature and you are still considered as being "on your route".

All other features – On all other types of non road/trail terrain you may travel **15 meters to either side** of your marked route and you are still considered as being "on your route".

APPENDIX C. CONSENT FORMS
1. PRIVACY ACT STATEMENT

NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA 93940
PRIVACY ACT STATEMENT

1. Authority: Naval Instruction

2. Purpose: Collaborative navigation and wayfinding will be studied to enhance knowledge, or to develop tests, procedures, and equipment to improve the development of Virtual Environments.

3. Use: Collaborative navigation information will be used for analysis by the Departments of the Navy and Defense, and other U.S. Government agencies, provided this use is compatible with the purpose for which the information was collected. Use of the information may be granted to legitimate non-government agencies or individuals by the Naval Postgraduate School in accordance with the provisions of the Freedom of Information Act.

4. Disclosure/Confidentiality:

    a. I have been assured that my privacy will be safeguarded. I will be assigned a control or code number, which thereafter will be the only identifying entry on any of the research records. The Principal Investigator will maintain the cross-reference between name and control number. It will be decoded only when beneficial to me or if some circumstances, which is not apparent at this time, would make it clear that decoding would enhance the value of the research data. In all cases, the provisions of the Privacy Act Statement will be honored.

    b. I understand that a record of the information contained in this Consent Statement or derived from the experiment described herein will be retained permanently at the Naval Postgraduate School or by higher authority. I voluntarily agree to its disclosure to agencies or individuals indicated in paragraph 3 and I have been informed that failure to agree to such disclosure may negate the purpose for which the experiment was conducted.

    c. I also understand that disclosure of the requested information, including my Social Security Number, is voluntary.

_

Signature of Volunteer   Print Name, Grade/Rank   DOB   SSN   Date

Signature of Witness   Date

75

2. MINIMAL RISK CONSENT STATEMENT

NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA 93943

MINIMAL RISK CONSENT STATEMENT

Subj: VOLUNTARY CONSENT TO BE A RESEARCH PARTICIPANT IN: COLLABORATIVE NAVIGATION AND WAYFINDING

1. I have read, understand and been provided "Information for Participants" that provides the details of the below acknowledgements.

2. I understand that this project involves research. An explanation of the purposes of the research, a description of procedures to be used, identification of experimental procedures, and the extended duration of my participation have been provided to me.

3. I understand that this project does not involve more than minimal risk. I have been informed of any reasonably foreseeable risks or discomforts to me.

4. I have been informed of any benefits to me or to others that may reasonably be expected from the research.

5. I have signed a statement describing the extent to which confidentiality of records identifying me will be maintained.

6. I have been informed that since the risks are minimal any injury I suffer while participating in the experiment will be at my own risk and that I accept full responsibility for my own medical treatment.

7. I understand that my participation in this project is voluntary, refusal to participate will involve no penalty or loss of benefits to which I am otherwise entitled. I also understand that I may discontinue participation at any time without penalty or loss of benefits to which I am otherwise entitled.

8. I understand that the individual to contact should I need answers to pertinent questions about the research is Rudy Darken, Ph.D., Principal Investigator, and about my rights as a research subject or concerning a research related injury is the Modeling Virtual Environments and Simulations Chairman. A full and responsive discussion of the elements of this project and my consent has taken place.

| Signature of Principal Investigator | Date |

| Signature of Volunteer | Date |

| Signature of Witness | Date |

3. CONSENT FORM

1. **Introduction.** You are invited to participate in a study of spatial awareness of natural and virtual environments. With information gathered from you and other participants, we hope to discover insight on navigational aids used to move through virtual environments during dismounted navigation of natural terrain. We ask you to read and sign this form indicating that you agree to be in the study. Please ask any questions you may have before signing.

2. **Background Information.** The Naval Postgraduate School NPSNET Research Group is conducting this study.

3. **Procedures.** If you agree to participate in this study, the researcher will explain the tasks in detail. There will be two sessions: a) 30 minute introduction phase and 2) training and execution phases lasting approximately four hours in duration, during which you will be expected to accomplish a number of tasks related to navigating natural terrain.

4. **Risks and Benefits.** This research involves no risks or discomforts greater then those encountered in ordinary hike through rolling, wooded terrain. The benefits to the participants are practicing land navigation and orienteering skills and contributing to current research in human-computer interaction.

5. **Compensation.** No tangible reward will be given. A copy of the results will be available to you at the conclusion of the experiment.

6. **Confidentiality.** The records of this study will be kept confidential. No information will be publicly accessible which will possibly identify you as a participant.

7. **Voluntary Nature of the Study.** If you agree to participate, you are free to withdraw from the study at any time without prejudice. You will be provided a copy of this form for your records.

8. **Points of Contact.** If you have any further questions or comments after the completion of the study, you may contact the research supervisor, LCDR James E. Boswell, at (408) 656 – 4071 (Email: jeboswel@cs.nps.navy.mil).

9. **Statement of Consent.** I have read the above information. I have asked all question and have had my questions answered. I agree to participate in this study.

_____   _____
Participant's Signature   Date

_____   _____
Researcher's Signature   Date

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APPENDIX D. BRIEFING SCRIPTS
1. PLANNING IN-BRIEF

In front of you is a 1:5000 and 1:24000 map of an orienteering course. You also have a satellite photo of the area. These tools are for your use to study and plan the route you will be using to navigate the course.

You have thirty minutes to study the map. Your planned route must navigate you through the nine checkpoints in order. (Show the subject the checkpoints in order.) Beginning at the designated starting point, you will go to CP1, then to CP2, then to CP3, ... and finally to CP9. The checkpoints are described in the clue sheet provided. You do not have to follow the blue lines between checkpoints, just navigate to the checkpoints. You may take the task listing with you when you go on the course. Before the end of the thirty-minute study phase, you will mark your planned route on the map using a red alcohol marker.

(Demonstrate a control marker)

After thirty minutes, you will be taken to the navigation course to run the route you designated on your laminated map. While navigating the course, you will navigate without the map or compass as much as possible. You will perform a map and compass check at each waypoint. There are notional gun emplacements on the course, when you have identified a gun emplacement you will be given a blue marker and the map to designate its location as accurately as possible. During the execution of the course, you may request a map and compass check. You can request as many map or compass checks as you wish, but each check will be recorded. If you decide to deviate from your previously planned route, you may request the map to mark your newly planned route. If you are off course for more than five minutes I will notify you and give you the map so you can plan a new course.

Do you have any questions before we begin?

2. THINK OUT LOUD INSTRUCTIONS

Think Out Loud Instructions

Your thoughts are important to this research. As you navigate the course you should be talking with each other as much as possible and "thinking out loud".

As you move through the environment and experience it directly express what you are thinking. The mental preconception you had of this environment before you stepped into it will now be evaluated by you as you experience the course directly. As this image is confronted with direct experience your expectations and plan may be confirmed, modified, or refuted. Be sure to talk out loud about these thought and compare your expectations with your partner.

The process of talking out loud and paying close attention to your route will slow you down. This is expected.

PLEASE SPEAK LOUDLY SO THAT YOUR VOICE WILL BE PICKED UP BY THE MICROPHONE

APPENDIX E. COURSE

1. CONTROL POINT PHOTOS

CONTROL POINT ONE
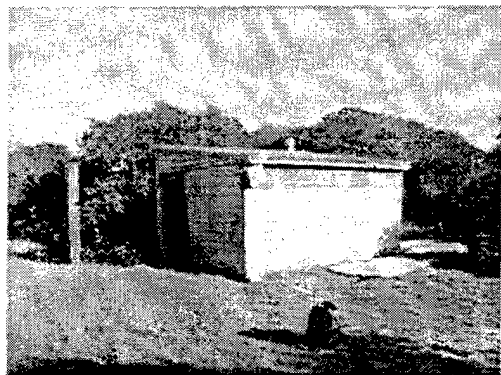
CONTROL POINT ONE
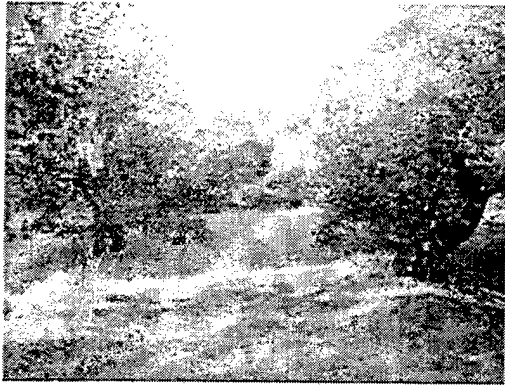

GUN POSITION ONE

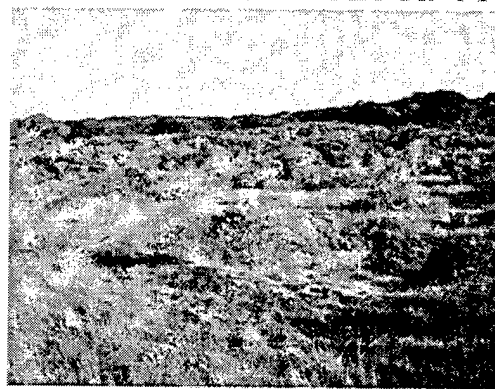CONTROL POINT TWO

CONTROL POINT THREE

CONTROL POINT THREE

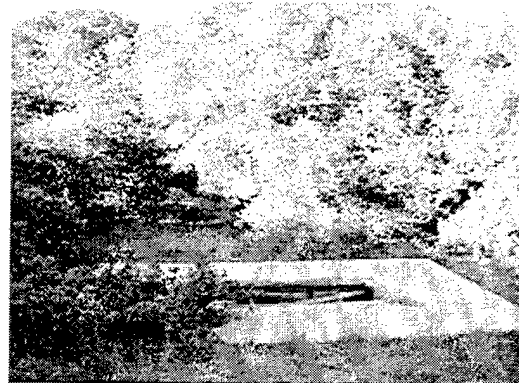GUN POSITION TWO

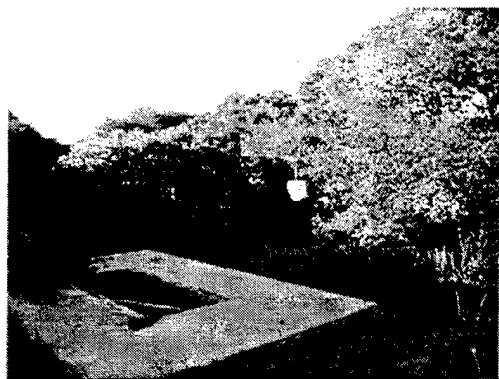CONTROL POINT FOUR

CONTROL POINT FOUR
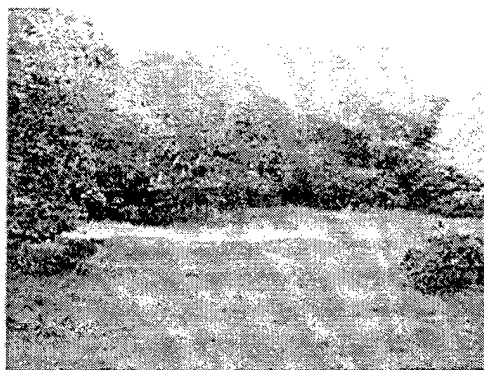
CONTROL POINT FIVE

CONTROL POINT FIVE

CONTROL POINT SIX

CONTROL POINT SIX

GUN POSITION THREE

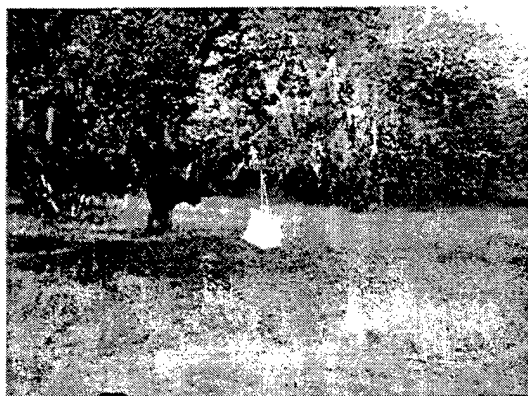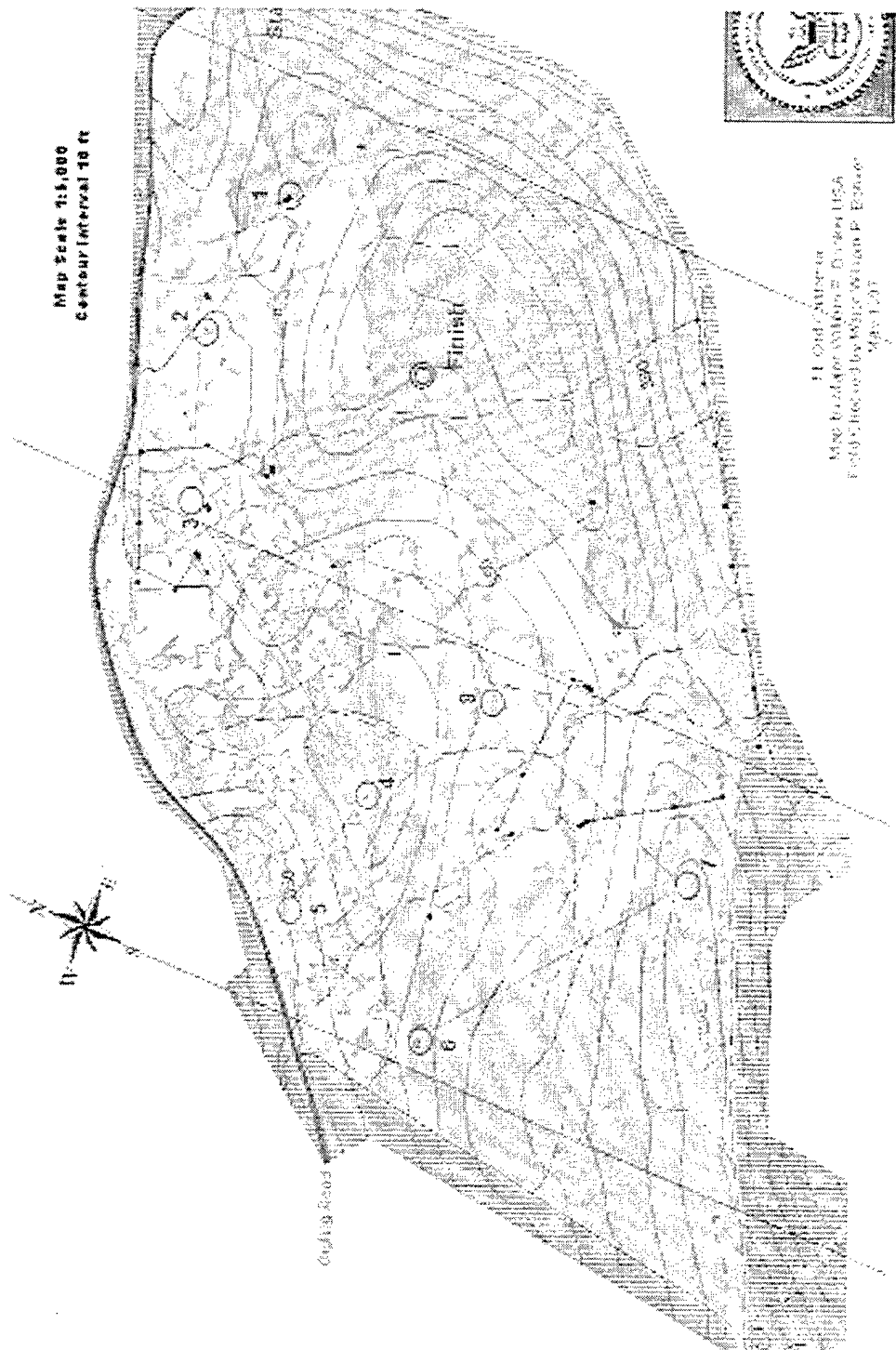CONTROL POINT SEVEN

CONTROL POINT SEVEN
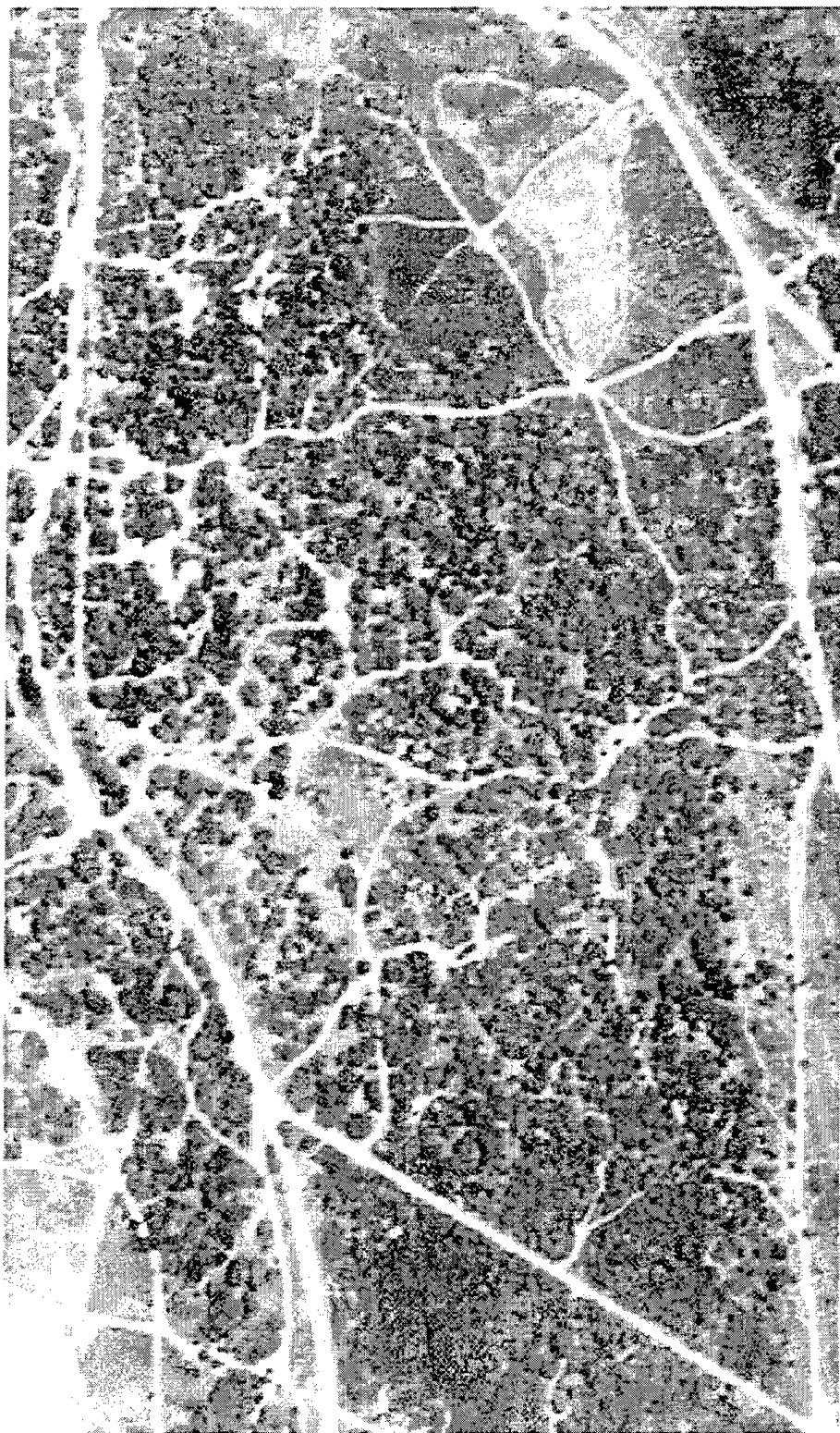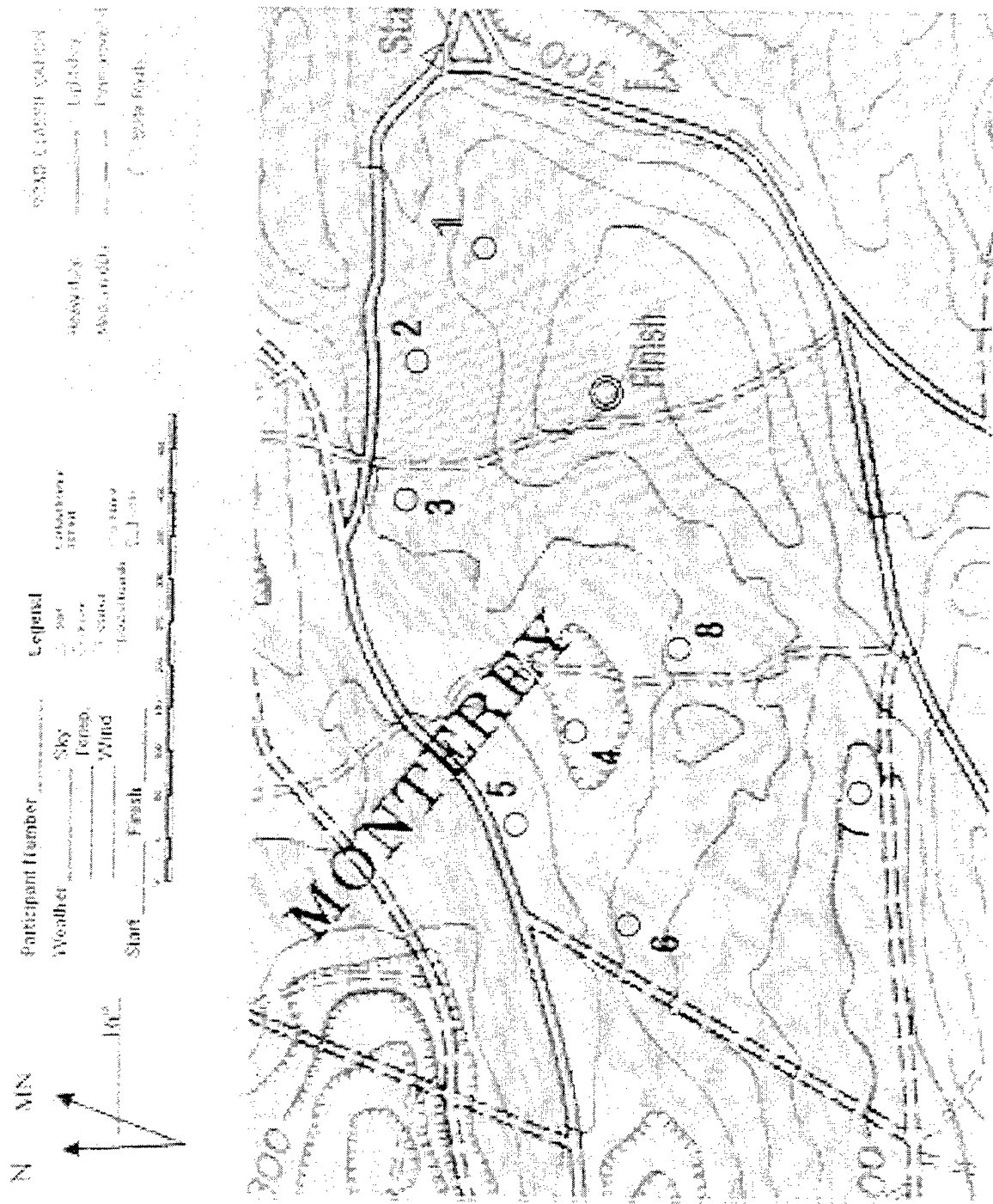
CONTROL POINT EIGHT

CONTROL POINT NINE

2. COURSE MAP

3. COURSE PHOTO

4. COURSE MAP (1:24000)

MAP DATA from 1:24,000 Enlarged to 1:5,000

APPENDIX F. DEBRIEF INTERVIEW SHEETS
1. CRITICAL DECISION POINT METHODOLOGY

Set-up video camera to record interviews.

Step 1. Select Incident: While in the field select incidents that can illustrate non-routine aspects of wayfinding, such as; errors in navigation, disagreement between team-members, map-checks.

Incidents (identified by administrator):

1_____

2.

3.

Step 2. Obtain Unstructured Incident Account: Have the subjects discuss the incident from start to finish with each other and with the intent to explain as completely as possible everything that affected their actions from start-to-finish. (Video for analysis)

1.

2.

(blank lined response area)

3.

(blank lined response area)

Step 3. Decision Point Probing. These questions are intended to elicit the basis of any decisions identified as central to the critical incident? The can include, but are not limited to the following?

Ask subjects to draw a diagram of the area, and provide the location and description of significant cues.

Discuss prior knowledge of this type of situation. Did subject compare the situation to previous way-finding situations?

Elicit the goal structure of the situation. What goals were considered and in what order?

What options were considered at this point?

Were methods of gaining additional information considered? If so, what methods?

What was the basis of selecting among the options? Can a rule be stated?

2. SIMULATION INTERVIEW SHEET

Events	Actions	Situation Assessment	Critical Cues	Potential Errors

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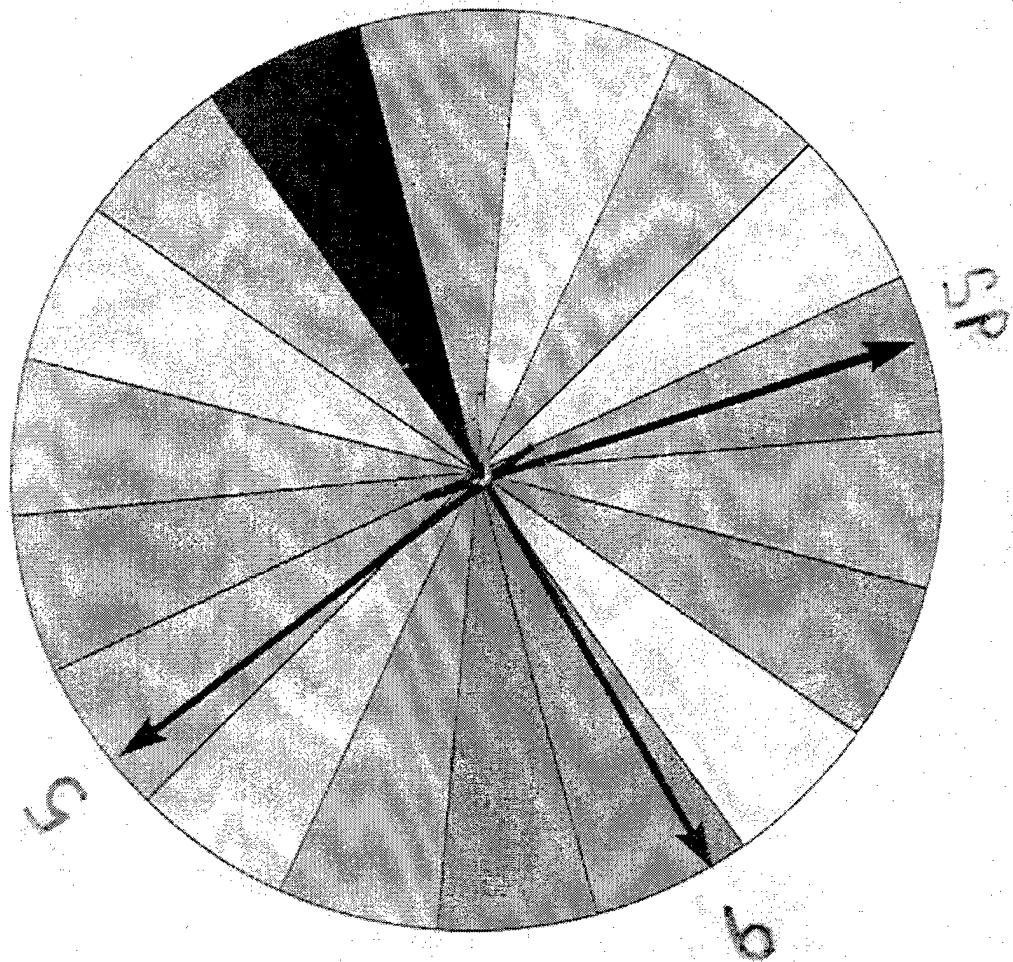
8.1 Boor
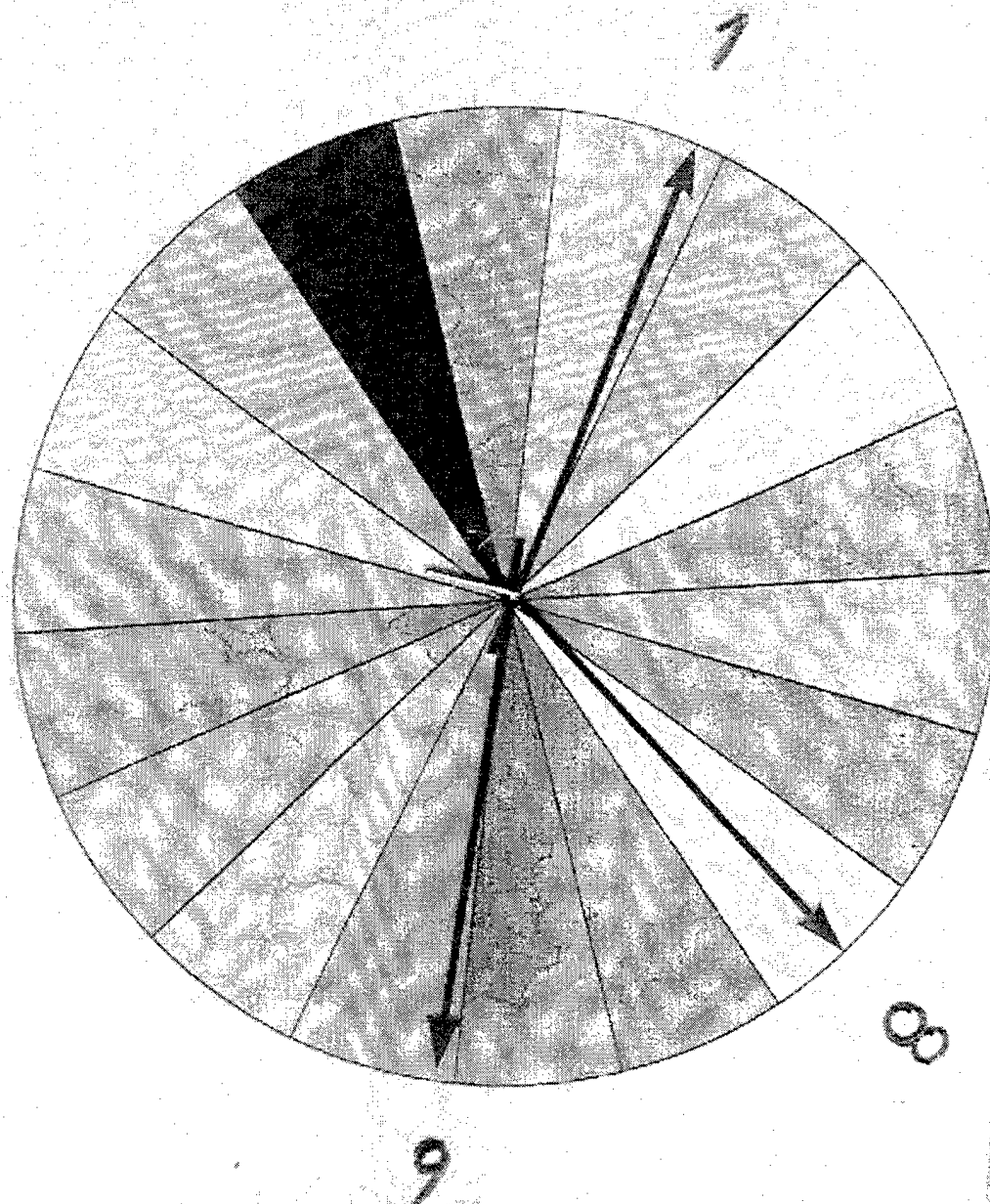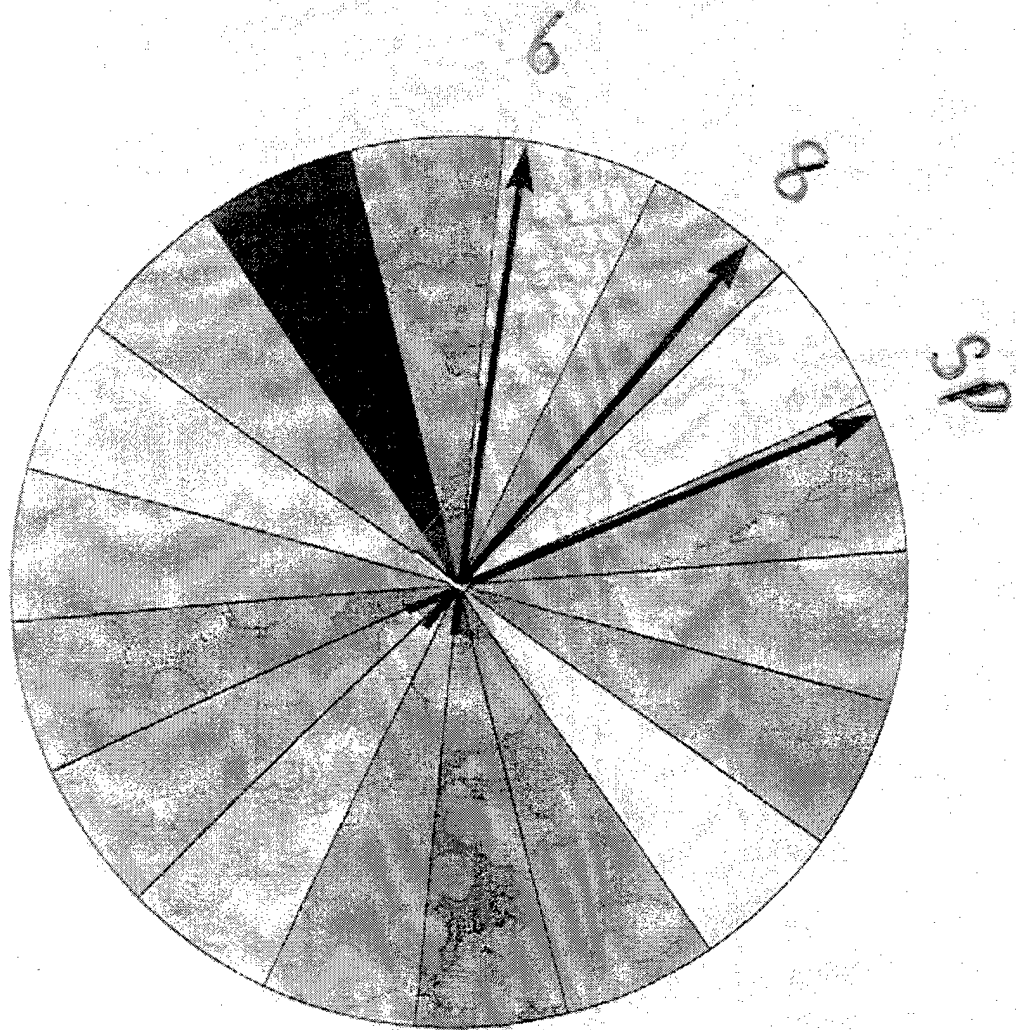
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